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A Building System Based on Foamed Concrete Cast Between Stay-in-Place Cement-Board Forms

by

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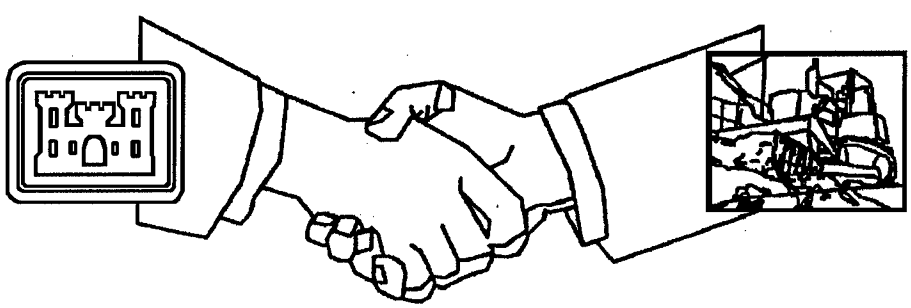

A Corps/Industry Partnership to Advance Construction Productivity and Reduce Costs

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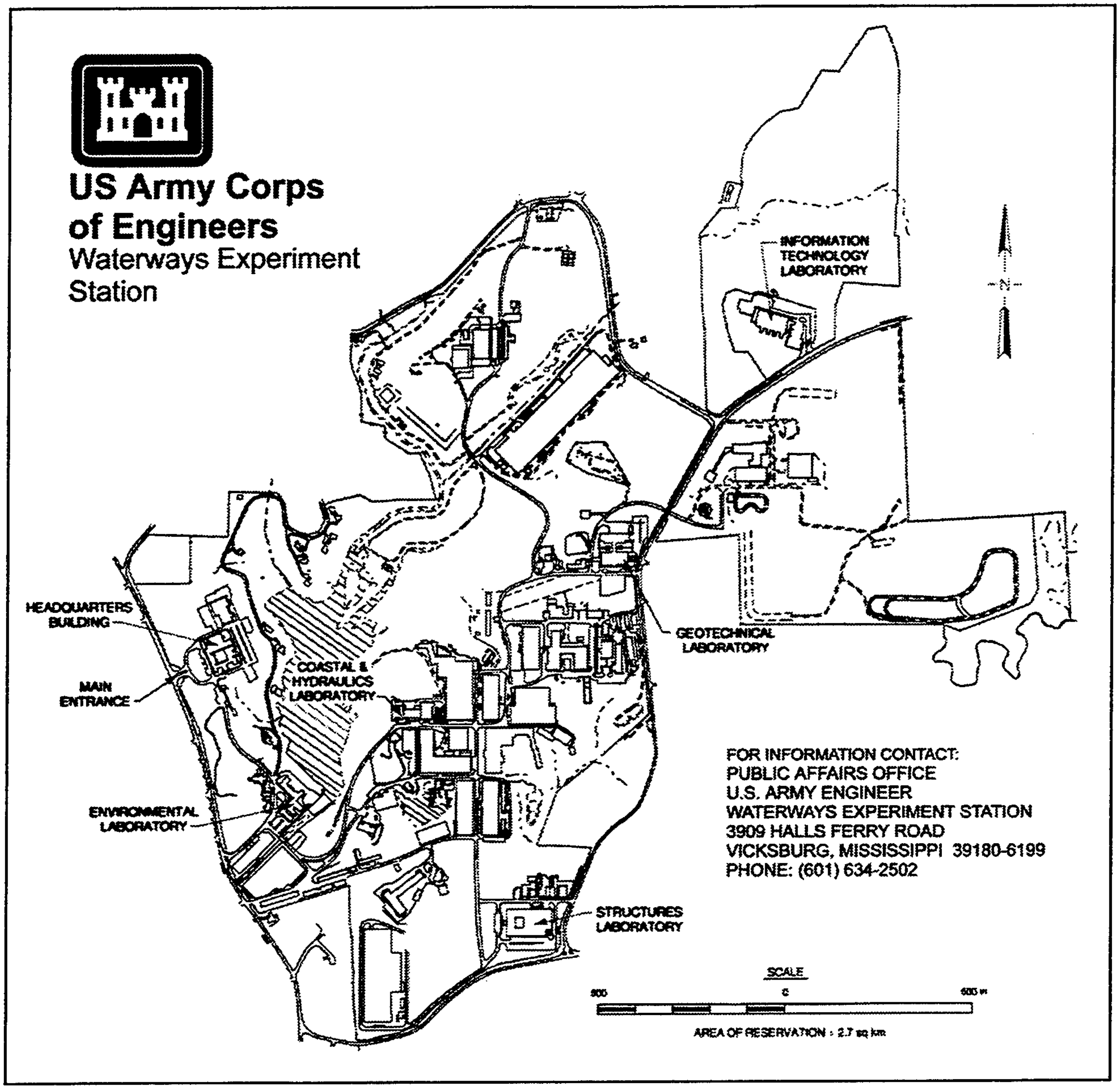

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Preface

This report was prepared at the Structures Laboratory (SL), U.S. Army Engineer Waterways Experiment Station (WES), under the sponsorship of Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Construction Productivity Advancement Research (CPAR) Program. The investigation reported in this document was conducted under a Cooperative Research and Development Agreement between WES and Materials Technology Ltd. (MTL), Reno, NV. The HQUSACE Technical Monitors were Messrs. Daniel Chen (CEMP-ET) and C. Gutberlet (CEMP-ET).

The study was conducted under the general supervision of Mr. Bryant Mather, Director, SL; Mr. John Ehrgott, Assistant Director, SL; and Dr. Paul F. Mlakar, Sr., Chief, Concrete and Materials Division (CMD), SL. Mr. William F. McCleese, SL, was the CPAR point of contact at WES. Dr. Philip G. Malone, CMD, was the Principal Investigator of this work unit. Dr. Malone, Mr. Joe G. Tom, and Dr. William N. Brabston, CMD, and Mr. Roger H. Jones, Jr., MTL, prepared this report. The investigation at MTL was conducted by Mr. Jones.

At the time of the publication of this report, Dr. Robert W. Whalin was the Director, WES. COL Robin R. Cababa, EN, was the Commander.

1 Introduction

In January 1995 a Cooperative Research and Development Agreement (CRADA) was initiated between Materials Technology Ltd. (MTL), Reno, NV, and the U.S. Army Engineer Waterways Experiment Station (WES) under the Construction Productivity Advancement Research (CPAR) Program to develop a new system of building walls for residential and light-utility buildings. The new approach used stay-in-place, fiber-reinforced cement-board forms with foamed or cellular concrete cast between the forms. An immediate goal of the research was to prepare a formulation for cellular concrete that could be cast between cement-board forms in lifts as high as 2.42 m (8 ft) and to optimize the mixture in terms of cost and strength. The project also involved investigating the compatibility of the formulation that was developed with the cement board and developing the optimum system for placing the foamed concrete in the forms. WES collaborated with the industry partner in developing an improved panel spacer and form tie system and further assisted by developing a versatile, low-cost panel fastening system that can be used with the stay-in-place forms. Because of the potential benefits of this developing technology for both the Federal Government and the private sector, this research on a new building system was well-suited to the CPAR Program.

Objective

This CPAR project was undertaken to test, demonstrate, and commercialize a new construction system for buildings. The new system employs stay-in-place forms made from fiberglass-reinforced cement boards. The forms are erected in a specially designed concrete foundation and then filled with foamed concrete. The project included wall units and the systems for joining and anchoring the units.

Approach

The work was divided into eight phases that typically involved contributions from both partners. The initial efforts (Phases 1 and 2) involved the

determination of the best construction components and the performance of these materials under a range of placement conditions. Phase 3 involved the optimization of the foamed concrete composition to obtain the strongest foamed concrete that could be placed under normal construction conditions. Phase 4 efforts concentrated on the optimization of adhesive systems for bonding form panels and the development of form tie systems. Phase 5 involved the construction and evaluation of a full-scale wall section (foam-filled panel pair). Phase 6 efforts were directed to the documentation of the wall system. Phase 7 involved the construction of a wall section with interior reinforcement and form ties as a demonstration of the constructibility of the wall system. The final phase, Phase 8, was directed to the commercialization on the wall construction system.

Background

Foamed concrete is also referred to as aerated or cellular concrete. Foamed concretes are lightweight concretes that are prepared by adding air cells (Figure 1) to the concrete paste at some point in its manufacture. The air cells typically range from 0.1 to 1 mm (0.004 to 0.04 in.) in diameter (Aldrich and Mitchell 1976). The air cells ideally are robust enough to survive in the mixture during transportation, placement, and hardening of the concrete. Foamed concretes are typically manufactured with densities ranging from 320 to 1,920 kg/m^3 (20 to 120 lb/ft^3).

The foamed concrete used in this investigation was a 500- to 880-kg/m^3 (31- to 55-lb/ft^3) mixture that did not contain aggregate. Admixture materials, dispersing agents, chopped synthetic fiber, and pozzolans were added to the foamed concrete to improve the strength and toughness and produce a more uniform material. The particular type of foamed concrete prepared for this research program would be classed as a neat-cement cellular concrete modified with admixtures (Legatski 1994).

Foamed concrete is a desirable material in construction because of its durability, thermal-insulating, and fire-retarding properties. The low density of foamed concretes produces a substantial reduction in the dead weight of the structures in which it is used. Savings are also realized in the reduced mass of materials that have to be brought to the building site.

Foamed-concrete panels are considered an economical component in construction because they are not subject to attack by insects or fungi. Foamed concrete will not degrade or depolymerize because of oxidation or photolytic reactions. In the event of fire, foamed concrete will slow the spread of the fire and will not emit smoke or toxic fumes (Short and Kinniburgh 1981, 1978).

As the density of foamed concrete decreases, the strength properties and thermal conductivity decrease (Figures 2 and 3). Foamed concretes are

generally used in nonstructural applications such as roof decks over metal formwork, void-filling grouts, and shock-absorbing materials for special applications.

Foamed-concrete blocks or panels are produced as cast-in-place (or cast-onsite) or precast units. Precast blocks or panels are generally manufactured by using chemical additives to generate gas bubbles in the concrete mixture. Precast operations for conventional construction blocks require a plant with special mixing equipment; curing is typically done under high-pressure steam. The most common precast items are aerated-concrete masonry units.

Cast-onsite operations typically use rotating drum or paddle mixers. The cellular structure is produced by introducing a preformed, aqueous-based foam similar to a fire-fighting foam. Curing follows practices similar to conventional nonfoamed concrete.

Both approaches to using foamed concrete have advantages and limitations (Schierhorn 1994). Precast units typically:

a. Are manufactured to consistent specification and arrive at the jobsite with well-defined strengths and densities as precisely dimensioned blocks or panels.

b. Are subject to breakage during transportation and wall-fabrication due to their low compressive strengths.

c. Require adjustment in masonry-laying practices to accommodate the large sizes and wide joints used with the light blocks and panels.

d. Are solid units and have no cavities for metal reinforcement or installation of utilities.

e. Require the same skill levels as are required for conventional masonry construction since it is still necessary to hold the wall plumb as it is installed and to meet the finishing criteria that are required for a conventional concrete block wall.

f. May require formwork for conventional concrete to be placed if the regional building codes require that the tie-beam at the top of a wall be rigidly attached to the foundation.

g. May require a crane and crane operator to be onsite if large precast panels are used.

The new method of using cast-in-place foamed concrete with stay-in-place forms that is the subject of this project offers several advantages. The cast-in-place construction with stay-in-place forms can be adapted to a variety of requirements, and the new construction system:

a. Requires quality control on the foamed concrete that is produced onsite. Quality control must be approximately that specified for the installation of any cast-in-place foamed concrete that might be placed as a fire wall or as a roof deck.

b. Does not require transportation of fabricated foamed-concrete blocks or panels that are subject to breakage during shipment.

c. Uses standard practice for placing foamed or conventional concrete in forms.

d. Allows hollow spaces to be blocked out in the walls for the installation of utilities or for steel-reinforced concrete pilasters that are integral with the wall.

e. Requires no craftsmen with masonry skills.

f. Does not require that a crane and crane operator be onsite to lift preformed panels into place.

2 Development of Foamed-Concrete Mixture Proportions and Preparation Procedures

The strength of foamed concrete made with conventional portland cement can be maximized by combining the mixture design that offers the highest paste strength with the optimum mixing techniques. Previous engineering studies (Pier and Pahl 1994) show that for a given density of foamed concrete, the strength of the cured foam concrete increases as the strength of the cured paste increases (Figure 4). High-strength concretes designed with conventional materials typically improve the strength of the cured concrete by reducing the water/cement ratio (w/c) using a high-range water-reducing admixture (HRWRA) and by replacing up to 15 percent of the mass of cement with silica fume. In a conventional nonfoamed concrete, the decrease in the void space that is produced by a lower w/c accounts for the increased strength. The addition of silica fume as a replacement for cement allows the calcium hydroxide formed by the hydration of the cement to react and form additional calcium silicate hydrate gel that increases the strength of the paste. The design strategy used in this study involved investigating a silica-fume replacement of up to 15 percent and the use of high-range water reducers that allowed samples with w/c's as low as 0.44 to be prepared.

Pier and Pahl (1994) also found that the strongest foamed concretes were made without using any fine aggregate. The fine-aggregate particles acted as stress concentrators, and samples made with any fine aggregate were weaker than the neat-cement formulations. No fine aggregate was used in the mixtures prepared in this study. An organic fiber (nylon) was used in the mixture in quantities that are approximately 1 percent by volume of the mixture. The fiber was added to increase the fracture toughness of the mixture.

Other less well-defined factors that affect the strength of foamed concrete were also observed in past investigations. The character of the foaming agent (synthetic organic or various types of hydrolyzed protein) can produce

significant changes in strength (Pier and Pahl 1994). Animal protein-based foaming agents and synthetic foaming agents were both evaluated in this study.

The type of mixing equipment employed has also been considered as an important variable in producing the optimum strength. Mixers (such as high-shear blade mixers or colloidal mixers) that produce the most thorough wetting of the cement are thought to produce the highest strength concretes. These effects have to be approached empirically, and selection of ingredients and equipment has to be based on laboratory trials. In this investigation, the investigators examined several different types of mixers and developed a technique for mixing that involved the use of a high-shear mixer to make a paste and a paddle mixer to blend foam and fiber with the paste. The steps used in making the concrete are shown in diagram form in Figure 5.

Methods and Materials Used in the Column Tests

Initial trials with 2.42-m- (8-ft-) tall columns were run using a series of mixtures presented in Table 1. Three important variables, the proportion of silica-fume replacement, the type of HRWRA, and the w/c, were evaluated in this series. A methocellulose thickening agent (Methocel F4M, Dow Chemical Co., Midland, MI) was added to each batch to reduce the rate of settling of the cement particles. The mixing operation followed the manufacturer's recommended procedure that involved dry blending the Methocel with portland cement in a 7-to-1 by volume mixture prior to adding the cement to the water in the high-shear mixer. The paste was prepared by combining the water, HRWRA, dispersing agent, cement, and silica fume in a 0.36-m^3 (12-ft^3) capacity high-speed shear mixer. The addition of foam adds water to the mixture, and the quantity of the water depends on the density of the foam. The amount of water that could be added in the cement-water mixture in the high-shear mixer was restricted by the amount of water that would be added when the foam component was mixed with the paste. In all cases, it was necessary to add sufficient water to the high-shear mixer to get the cement paste to mix efficiently and to flow out of the mixer.

A set quantity of paste was removed from the high-shear mixer and placed in a Stone Model 1265PM paddle mixer (Stone Construction Equipment Co., Honeoye, NY). Litecrete R11937 foaming agent (Insulcrete, Inc., Rosemead, CA) was used in all mixtures. The foaming agent was diluted 39 to 1 by volume, and the diluted solution was foamed using a Cellufoam Systems Model 620 Foam Generator (Cellufoam Concrete Systems, Scarbrough, Ontario, Canada). Foam was added to adjust the density to the target level, and fiber was added to the foamed concrete. The foamed concrete was then removed from the paddle mixer and placed in the form either by hand or by means of a ChemGrout Model GC-550 progressing cavity pump (Chemgrout Inc., La Grange Park, IL).

To prepare sample cylinders, the fresh foamed concrete was placed into waxed fiberboard cylindrical forms that had an inside diameter of 203 mm (8 in.) and a height of 2.42 m (8 ft). The sides of the forms were tapped with a mallet as the concrete was added. The top of the column was observed to detect any decrease in volume or dropping of the level of the foamed concrete in the cylinder. The top of the column was wrapped in polyethylene sheeting to prevent any loss of water during curing. After the concrete had hardened for 7 days, the columns were cut into six 406-mm- (16-in.-) long cylinders. Three of the cylinders were wrapped in plastic and placed in a 100-percent humidity room to cure for 28 days. The second set of three cylinders was used to obtain data on unconfined compressive strength after 7 days curing in a 100-percent humidity room. The two sets of three samples were collected in such a way that each set included one sample near the top of the column, one near the middle, and one near the bottom of the column. This procedure was followed so that any difference in properties that might be related to the position of the specimen in the top or bottom of the sample column would not affect the determination of the average strength of the concrete in the sample column.

Test Methods Used with Column Samples

After curing, the sample cylinders that were prepared from the sample column were stripped from the molds and trimmed to right cylinders. The ends of the cylinders were smoothed with emery cloth. The cylinders were permitted to air-dry for 24 hr and were measured and weighed. Unconfined compressive strengths were measured using the procedure outlined in American Society for Testing and Materials (ASTM) C 39 (ASTM 1993a). All cylinders were evaluated in an uncapped condition using an MTS Model 810 Material Testing System (MTS Systems Corp, Minneapolis, MN).

Results of Testing Using Columns

The results of the column testing are presented in Table 2. Silica-fume replacement above 20 percent presents problems with regard to water demand even when HRWRA is used. In two of the three attempts to place foamed concrete with a 20-percent silica-fume replacement, the foamed concrete collapsed. The most successful placements and highest strengths were obtained with 10-percent silica-fume replacement. The best flow characteristics and best strengths were obtained with a mixture that contained 10-percent silica-fume replacement and at w/c = 0.62. The HRWRA ingredient that performed best was Sikament S-10 ESL (Sika Corp., Lyndhurst, NJ). Sikament S-10 ESL is a synthetic HRWRA formulated around a vinyl co-polymer. The manufacturer recommends this HRWRA for use in concretes containing silica fume or other micro-silica products. The manufacturer's recommended addition rate is 390

to 1,300 ml/100 kg of cement. Additions of approximately 1,200 ml/100 kg of combined cement and silica fume were used in these analyses.

Typically, the samples from the lowest part of the column were 16 to 32 kg/m^3 (1 to 2 lb/ft^3) denser than the samples from the top of the column. In extreme cases, variations as high as 320 kg/m^3 (20 lb/ft^3) were noted. Denser samples are stronger. In these low-density concretes, a 16- to 32-kg/m^3 (1- to 2-lb/ft^3) density difference can increase the unconfined compressive strength by 100 kPa (14.5 psi) or more.

The mixture proportions that were carried into the evaluations using panel forms made from cement board all used 10-percent silica-fume replacement and Sikament S-10 ESL as the HRWRA. The target densities for the panels were set at 480 to 560 kg/m^3 (30 to 35 lb/ft^3) with target unconfined compressive strengths (28 days) of over 895 kPa (130 psi).

Tests of Foamed-Concrete Panels

This phase of the experimental work had the following goals:

a. Confirm that the mixture proportions used in the columns would be placed in larger volumes in the panels.

b. Determine the most suitable materials and methods to be used in coating the cement-board forms.

c. Develop the requirements for the supports for the concrete-board formwork.

d. Develop data on the temperature changes produced in the panels.

e. Develop a standard protocol for mixing and placing the foamed concrete in the formwork.

Methods and Materials Used in the Panel Tests

The panels were cast in such a way as to simulate a single 1.2-m- (4-ft-) wide section of cast-in-place wall that was 2.43 m (8 ft) high. The wall thickness was set at 140 mm (5.5 in.). Initial evaluations were run with the wall braced with horizontal walers set at 0.6-m (24-in.) intervals. The forms were made with 12-mm-thick cement board (Durock Exterior Cement Board, U.S. Gypsum Co., Chicago, IL, or equivalent). The cement board is flexible enough that the pressure from a few metres depth of foamed concrete will cause the forms to bulge if they are not braced with horizontal walers spaced

with a separation of 270 mm (10.5 in.) or less. Further, the cement board is porous, and the water in the foamed concrete filters through the cement board, effectively removing water from the mixture and causing the foam to collapse. The panels were constructed as full- (1.2-m-wide) or half-sized (0.6-m-wide) forms. All panels were coated on the inside or outside with two coats of latex-based sealer (Dow Latex CM 460 NA BK, Dow Chemical Co., Midland, MI). This sealer is formulated without adding any foaming control agents that might collapse the foamed concrete in contact with it. All seams in the form were caulked with acrylic sealer so that the forms were watertight.

The foamed concrete used in the making of the panel sections was proportioned and mixed in a manner similar to the concrete used in the column samples. The compositions of the concrete mixtures used are presented in Table 3. The concrete was placed in the forms by hand with buckets or by means of a small progressive cavity pump. The formwork was struck with a mallet during the filling process to minimize the air holes. After the forms were filled, the tops of the forms were covered with plastic sheeting to reduce water loss.

Testing Methods Used with Panel Samples

After the foamed concrete had cured for 7 days in the forms, the form with the concrete inside was cut apart. Blocks approximately 155 mm (6 in.) wide and 410 mm (16 in.) long were cut along the length of the panel (top to bottom). Each block was trimmed into three pieces. The concrete board was removed from each of the pieces, and a 127-mm (5-in.) cube was trimmed from each piece. This procedure provided three sample cubes from each 406-mm (16-in.) vertical interval on the panel. The sample cubes were air-dried, measured, and weighed, and the unconfined compressive strengths of the cubes were determined using the unconfined compression testing procedure outlined in ASTM C 109 (ASTM 1993b) using a MTS Model 810 Material Testing System (MTS Systems Corp, Minneapolis, MN). The cutting, trimming, and testing procedure was repeated after the panel had cured for 28 days.

Mixture Proportions Used in Panels

Initial efforts to place the foamed-concrete mixtures that were developed in the column study in larger forms were only partly successful. Of the 17 specimens prepared as panels, the foamed concrete collapsed in 7 cases (Table 4). The major difference between the concrete in the columns and in the panels was the total mass of concrete placed. The foamed concrete formulation is a very cement-rich mixture with no aggregate. The large proportion of cement (278.5 kg/m^3 or 472 lb/yd^3) and the low heat capacity of the mixture make the peak temperature during setting rise well above ambient

temperatures. The cement-board formwork also slows the dissipation of heat from the setting concrete. An effort was undertaken to measure the peak temperatures in both the columns and in the panels to determine if the temperature differences would explain the difficulty in using the same concrete formulations in both types of samples.

Temperature Measurements in Columns and Panels

An Omega Model 205 Temperature Logging System (Omega Engineering, Inc., Stamford, CT) was used with iron-constantan thermocouples to measure the temperatures in the setting foamed-concrete mixture when it was placed in columns and in panels. In the columns, the thermocouples were placed at 406-mm (16-in.) intervals down the length of the vertical column. Thermocouples were inserted through holes in the columns, and the measurements were made in the center of the fresh concrete. One thermocouple from each array was used to measure the ambient temperature in the laboratory. Data were taken on seven columns. During one of the column tests (No. 19), the foamed concrete collapsed. The ambient laboratory temperatures and the peak temperatures in the columns are given in Table 5.

The panels were instrumented for temperature measurement by drilling through the front of the form and inserting the thermocouples to a depth of 70 mm (2.75 in.). Three panels were instrumented using the thermocouple placement pattern shown in Figure 6. One additional thermocouple was used to measure the ambient temperature in the laboratory. A plot of the temperature records for the thermocouples for Test No. 25 (placed on 18 August 1995) is presented in Figure 7. The highest temperatures were consistently observed in the center of the panel form (thermocouple location 9 in Figure 6).

The ambient laboratory temperatures and the peak temperatures in the panels are also given in Table 5. The peak temperatures recorded in the columns ranged from 36 to 40 °C. The average peak temperature in the columns was 38.1 °C. Peak temperatures recorded in the panels ranged from 52 to 54 °C with an average peak temperature at 53.3 °C.

The concrete in the panels was generally 14- or 15-centigrade degrees higher at its peak temperature than the concrete in the columns. A high temperature can cause the foam to collapse because it expands the gas bubbles in the concrete and lowers the surface tension in the foam. Based on the results of the temperature measurements, a synthetic foaming agent that was considered to have better tolerance at high temperatures was substituted for the animal protein-based foam that had been used in the columns and in the panels where the foamed concrete had collapsed. The formulation that was produced for the last panel test series (Tests 39-43) used foam produced using Cellufoam

Systems WF-304 foaming agent (Cellufoam Concrete Systems, Scarbrough, Ontario, Canada).

Results of Testing Using Panels

The results of the tests of the foamed concrete cast in the cement-board forms are summarized in Table 4. The best and most reproducible foam samples were those produced in Tests 42 and 43. This formulation for the concrete met all of the criteria that had been objectives for this portion of the study. The goal was to produce materials that had an air-dried density under 640 kg/m^3 (40 lb/ft^3) and an unconfined compressive strength of over 690 kPa (100 psi) after curing for 28 days, and could be placed in lifts as deep as 2.42 m (8 ft). The materials produced in Tests 42 and 43 had an average density of 577 kg/m^3 (36.0 lb/ft^3) and an average unconfined compressive strength of 1,056 kPa (153.3 psi) at 7-days age and an average unconfined compressive strength of 1,530 kPa (222.0 psi) at 28 days. All of the panels prepared with this mixture cured without any significant collapse when cement-board forms coated with latex were used. The composition used in the optimum mixture proportion is presented in Table 6.

Methods of Foamed-Concrete Placement

Moving foamed, fiber-reinforced concrete from the mixer to the forms requires some care to avoid separation of materials and densification of the concrete due to bubble collapse. In this study, pumping systems were found to be troublesome in that the pumps can increase the density of the concrete. In the small, progressive cavity pumps that were tested, the densities would typically be increased by 80 to 90 kg/m^3 (5 to 6 lb/ft^3). Foamed concrete can become moderately viscous, and the flow from the feed hopper into the pump did not always keep up with the pump. Cavitation would occur, and voids would appear in the placed concrete. Progressive cavity pumps were found to be inconsistent in their ability to handle fiber. Fiber accumulations were frequently found in the pumps after placement was completed. It was found that any placement system that involved moving the concrete through a tube, such as in a pump or tremie, produced a skin on the concrete and the cured concrete would show smooth surfaces on fracturing. These failure surfaces resembled cold joints in conventional concrete (Figure 8). Examination of the surfaces showed that the fibers embedded in the concrete generally did not cross the surface. Attempts at mixing or rodding the foamed concrete after placement to eliminate the irregularities failed because of problems in moving the concrete in the form. The best placement system involved discharging the fluid mixture directly into the top of the formwork. The momentum of the fluid dropping into the form produced enough mixing to eliminate the obvious failure planes.

Methods of Coating Formwork

Two basic types of concrete or cement board are commercially available. One type is an 11- to 12-mm-thick panel made from a fine aggregate concrete and is reinforced with vinyl-coated fiberglass. Durock Cement Board (U.S. Gypsum Corp., Chicago, IL) is an example of this type of product. A second type of concrete or cement board also available in an 11-mm thickness is manufactured by combining mineralized cellulose fiber, portland cement, and mineral additives, and then hydrating and curing the mixture. An example of this type of product is Plycem Fiber-Reinforced Cement Board (U.S. Architectural Products, Inc., Lincoln, RI). Both products have porosities comparable to conventional portland-cement mortars. Both will absorb water and require coating if they are used as a durable exterior siding. Formwork made with these products will absorb water if it is not coated. Figure 9 shows the leakage that occurs when foamed concrete is placed in an uncoated, fiberglass-reinforced cement-board form. Water seeps through pore space and cracks in uncoated boards. Test runs showed that less collapse of the foamed concrete will occur if the panels are coated with a waterproofing material. The project investigated the use of two coats of latex sealer on the inside or outside of the cement board. In the forms made with panels coated on the exterior, the uncoated interior cement-board surface began to soak up water as soon as the foamed concrete was put in place (Figure 10), while boards coated on the interior surface remained dry (Figure 11). Forms where the concrete had shown negligible collapse were all covered on the interior with two coats of latex sealer.

Effects of Temperature on Panel Production

The peak interior temperatures in the panels reached approximately 30 °C above ambient temperatures. The temperature changes did not produce any thermal or shrinkage cracking. The foam collapse observed stopped when the synthetic foaming agent was used. No problems with regard to flash setting or loss of workability were noted in the temperature ranges observed in this study. This research suggests that no special procedures (such as cooling the ingredients) or the use of low-heat cements are needed in foamed-cement panel production for the panel sizes used in this investigation when ambient temperatures are on the order of 20 to 25 °C. The usual cautions with regard to concrete placement should be followed with foamed concrete. Generally, concretes are best placed at 10 to 15.6 °C (50 to 60 °F). Cooling the concrete generally will become necessary when the air temperature is 23.9 to 26.7 °C (75 to 100 °F). Many specifications for conventional concrete call for the concrete to have a temperature less than 29.4 to 35 °C (85 to 90 °F) at the time of placement. The limit should be established for conditions at the jobsite based on trial-batch tests at the limiting temperature rather than at ideal temperatures (Kosmatka and Panarese 1990).

Results from Panel Casting Trials

Work undertaken in the investigation of the foamed concrete indicated that:

a. The target strengths and densities could be reached with a properly formulated and properly prepared foamed-concrete mixture (Table 6).

b. The mixture was best placed by dropping the foamed concrete into the formwork without the aid of a pump or tremie tube. Any confinement of the concrete as it was dispensed into the formwork created a skin that became a potential failure plane when hardened concrete was stressed.

c. The foamed concrete was so fluid that the formwork for all practical purposes had to be watertight. Every seam had to be sealed with a caulk, and even small holes for form ties had to be plugged.

d. The cement board as supplied from the manufacturer was too porous to serve as a form for the foamed concrete. The loss of water from the concrete into the formwork caused the foamed concrete to collapse. All successful panel fabrication was done after the cement board had been coated on the inside with a latex sealer.

e. The cement-board form had to be braced so that it could contain a fluid column with a maximum pressure at the base of the column of approximately 15.3 kPa (320 psf) without bulging or distorting, if the foamed concrete was to be placed in the formwork in a single lift. Experience with several different types of cement board indicated that this would require supporting the board with braces that were spaced approximately 250 mm (10 in.) apart.

3 Development of Panel Design for Structural Wall Using Foamed Concrete

In order to produce a strong wall unit that could used in fabricating a building, it was necessary to develop the following design elements:

a. A method of reinforcing the footing or foundation under the wall and attaching the panels to the foundation.

b. A method of fastening the opposing exterior panels together with uniform spacing to produce a uniform wall thickness.

c. A method of splicing or joining adjacent exterior panels together to form a smooth continuous surface.

d. A method of adding steel-reinforced concrete columns inside the wall to tie the foundation to a supporting beam at the top of the wall.

e. A technique for producing hollow spaces in the wall that would allow utilities to be placed in the wall.

f. A method of producing a strong connection at the corners where two wall units are brought together.

g. A method of adding openings for windows and doors to the wall.

These problems were addressed by adding a folded or corrugated panel (separator panel) between the two outer concrete boards and using specially designed ties between the cement board exterior panels (U.S. Patent Office 1997a). The interior folded panel maintained a uniform separation between the exterior panels (Figures 12 and 13). The separator panel was sandwiched between the two exterior panels, and the tops of the corrugations on the separator panel were flat to provide an attachment and splicing surface for the exterior panels. The basic design resembled corrugated paperboard or

cardboard. The wall was divided internally into a series of tall, vertical compartments that shared common walls on two sides with the next compartment. The separator panels could be spaced out between the exterior panels so that the flattened tops of the corrugations provided surfaces that extended under the edges of adjacent panels and produced a splice that supported the joint where the panels met. The interior separator panels were linked together inside the wall panels by passing horizontal lengths of steel reinforcing bars through holes drilled into the parts of the panels that spanned the space inside the wall. The interior spacer panels were anchored by setting them into the concrete foundation below the wall. The length of reinforcing bar that joined the separator panel section along the bottom of the panels became the reinforcing bar that was cast into the foundation. In this way, the separator panels were firmly attached to and held erect by the concrete foundation or footing.

In places in the wall where no separator panel was positioned behind the exterior panels, the exterior panels were held to the proper spacing by using a tie bar that would not allow the panels to move inward or outward. The simplest design of the tie bar used to hold the wall together was a notched rod shaped so that the rod would slide through holes drilled in the exterior panels and could be pushed down so that the notches in the rod engaged the panels (Figure 14). The notches kept the exterior panels from bulging in or out. These same tie rods could be modified by making one notch slightly wider than the other so that the rod could be pushed through holes drilled through the exterior wall panels and through the flat portion of the top of the corrugation in the separator panel. In this way, one notch engaged the lower edge of the hole in an exterior panel while the other notch engaged the lower edge of a hole that passed through the other exterior panel and the lower edge of the hole in the separator panel holding the separator panel and the exterior panel tightly together and also holding the opposing panel in the proper position. The tie bars with small modifications could be used in places where the separator panel was present and placed where it was absent. In both cases, the tie bars held the wall panels at the proper spacing.

The separator panels divided the interior of the wall into vertical compartments that could be used as forms for conventional concrete pillars in the walls. Reinforcing bars could be attached to the lowest horizontal reinforcing bar and run up inside the corrugations in the separator panels. In this way, the separator panels served to provide the forms for the internal pillars, and reinforcing bars could be used to attach the foundation and the horizontal beam across the top of the wall. The corrugations could also be blocked off and left empty so that plumbing or wire could be run up and down in the wall.

Role of Foamed Concrete in Wall Design

The development of the separator panel concept changes the structural role of the foamed concrete in the wall. As first viewed, the wall panels and foamed concrete would be a composite structural unit with the foam being a part of a supporting member. In the separator panel design, the supporting members are the internal reinforced-concrete pillars. The foam serves as a filler that provides some strength to the wall unit but primarily adds to the fire resistance and insulation properties of the wall. The high strength of the foam is a benefit but not a necessity in the wall. Delamination of the foam and panel portion of the wall and slip surfaces in the foamed concrete will not affect the overall strength of the wall in any significant way. The modulus of rupture or the tensile strength of foamed concrete will always be low (10 to 20 percent of its compressive strength). The low tensile strength will limit the ability of the foam to bond the exterior panels together as a unit, but in the present design with the separator panel, this is not an important consideration. The foam can be formulated to provide the best trade-off of acceptable strength, insulation properties, and cost. The ability of the design to use a variety of simple foam formulations makes the wall more economical to build and reduces the skill levels and equipment required in preparing the foamed concrete for the wall.

Reinforcing the Wall Footing or Foundation

The foundation was reinforced using No. 4 (12-mm-diam) steel reinforcing bar placed horizontally and centered in the concrete footing placed under the wall. The bar was supported 50 mm (2 in.) above the bottom of the formwork for the footing (Figure 15) using commercially available wire chairs. The reinforcing bar in the footing was also used to support and anchor together the sheet-metal separator panels that fit inside the wall. Altogether, three reinforcing bars (one each at the bottom, middle, and top) were attached to the separator panels by passing the bars through holes drilled through the sections of the panels that would span the space between the exterior panels. The holes for the lower bar were drilled 25 mm (1 in.) above the bottom of the separator panels (Figure 16). This lower reinforcing bar and the lower ends of the separator panels were cast into the footing to anchor the wall and held the separator panels erect. The horizontal reinforcing bars were placed into the metal separator panels by first adding temporary braces across the panels and attaching them with sheet-metal screws (Figure 17). The steel reinforcement was inserted, and the panels were tilted up and braced vertically with the panels resting on the lower horizontal reinforcing bar that was supported by the chairs placed in the footing formwork. The spacer panels could then be adjusted in position to be true and plumb. Additional reinforcing bars that would extend vertically inside the wall were bent and attached to the horizontal bar at the base and wired to the central and upper pieces of horizontal reinforcing bar.

A 15-mm-thick strip of plastic was attached to the bottom of the spacer panels so that the lower surface of the plastic was 12 mm below the top of formwork for the footing. The plastic strips (Figure 18) served as blockouts to form grooves, 12 mm deep, along the front and back of the separator panels. These grooves held the lower edges of the exterior panels (Figure 19). By applying sealer in the bottom of the groove, it is possible to make the joint between the panels and the foundation watertight.

The footing was formed using a conventional concrete with coarse aggregate no larger than 9 mm in diameter. The concrete was consolidated, trowel-finished, and covered to allow it to cure for approximately 7 to 10 days. After sufficient strength was obtained, the bracing on the spacer panels could be removed, and the plastic strip could be removed from the groove in the footing.

Attaching the Exterior Panels to the Spacer Panels

The cement panels as supplied are typically not sufficiently impervious to hold foamed concrete, so all of the exterior panels had to be covered with two coats of latex sealer. The coated panels were erected by lifting the panels into place with the lower edge in the groove in the foundation that was formed by the plastic strip. The exterior cement-board panels were temporarily braced in place and marked for any trimming that would be necessary. The panels were sized so that the edges of the panel met laterally at a point near the center of the top of the corrugations on the separator panels. In this way, the edges of the panels pressed against a surface that could anchor each panel and serve as a splice between panels. As the construction proceeded, the exterior panels were attached to the separator panel by pegs and by gluing with a construction adhesive. Separator panels could be spaced out inside the wall in any way they were needed. The exterior panels are manufactured to be 1.3 m (4 ft) wide. The spacer panels could be positioned so that the distance from the center of one corrugation to the center of the next corrugation was a full panel width. Holes were drilled along the edges of the panels spaced at 250-mm (10-in.) intervals vertically. Notched tie rods (Figure 20) were inserted into the holes and pressed down so that they held the exterior panels to separator panels and also held the exterior panel on the opposite side of the wall at the proper spacing (100 mm (4 in.) from the inside surface of one panel to the inside surface of the opposite panel).

The exterior panels were braced in position against the separator panels and temporarily assembled. The exterior panels could then be removed by lifting the tie rods out. In this way, the wall was initially assembled and then dissembled, the adhesive was applied to the joints, and the wall was reassembled permanently. Similarly, when the adhesive was applied to the

inside of the edge of the panel, a strip of liquid sealer could be applied to the bottom of the panel to seal the panel into the groove in the top of the footing.

Attaching Adjacent Cement-Board Panels

The separator panels were formed from 1-mm- (0.04-in.-) thick galvanized sheet steel formed into channels. Adjacent cement-board panels were brought together over the top of the flat portions of the channels. The spacer panels served as a splice between the exterior panels. Holes were drilled on the edge of each panel, and pegs were inserted into the holes to provide a mechanical attachment to the panels.

Adjacent panels were set up with a 5-mm (0.2-in.) gap between the edges of adjacent panels. The gap was specified by the manufacturer to allow for any expansion of the panels. An elastomeric caulk was used to fill in the gap so that the surface could be given a smooth finish.

Adding Steel-Reinforced Concrete Columns Inside the Wall

Metal corner columns were formed by welding two Z-shaped metal panels to form a 100-mm- (4-in.-) wide square column (Figure 21). When the corner columns were lifted into position on the concrete footing, a length of reinforcing rod was placed inside each column. The bottom of the reinforcing rod was bent and attached to the lower reinforcing bar. The columns were attached to the foundation and the beam at the top of the panel.

Columns could also be set up inside the wall by overlapping the channel sections to form a box-like column. Vertical reinforcing rods could be added before the channel-shaped separator panels were overlapped.

Producing Hollow Spaces in the Wall and Adding the Upper Beam

After the exterior panels had been attached to the separator panels, the vertical spaces that were to be filled with foamed concrete were selected and any compartments that were to be left empty were blocked at the top of the separator panel by adding a piece of cement board and fastening the piece in place with sheet-metal screws through the metal separator panels. Foamed concrete was prepared and placed into the compartments that were not being used for concrete pillars. The foam was placed or pumped into the top of each compartment, and the sides of the wall were tapped to consolidate the foamed

concrete and remove any voids. The compartments were filled to the top of the separator panels, a level approximately 100 mm below the tops of the exterior panels (Figure 22). After approximately 3 days of moist curing the foamed concrete, all of the remaining open compartments were filled with a conventional concrete mixture, and the concrete forming the pillars was consolidated with a vibrator (Figure 23). After the concrete in the columns was consolidated, the upper beam was cast by placing conventional concrete above the top of the separator panels. The top of the hardened foam concrete supported the fresh concrete placed to form the horizontal beam. The concrete at the top of the form (the top surface of the horizontal beam) was screed off and given a trowel finish (Figure 24). The top of the form was covered with wet burlap, and the concrete was allowed to cure for 28 days.

Finishing the Wall

After the concrete in the wall had cured, the ends of the tie rods were trimmed off (Figure 25). This is relatively easily accomplished using an abrasive disk on a hand-held drill motor. A power sander could be used to smooth down the wall surface. Any finish that is recommended by the cement-board manufacturer should be acceptable for this wall system. This selection would include a variety of paint and stucco systems. The latex coating applied to the cement board will generally be an acceptable undercoat for the surface finish. If it is necessary to remove the latex from the exterior surface, light sanding should be all that is needed.

Forming Windows and Doors

Windows and doors installed in conventional cast-in-place concrete can require unusual formwork. Foamed concrete has the advantage of being easy to cut away and remove. The simplest method of producing openings in a foamed concrete wall is to cast a complete wall and then use a masonry saw to cut openings in the wall after the concrete has cured. The casting-and-cutting technique guarantees that the concrete is continuous in critical points such as under window frames and above doors. Separator panels and pilasters can be arranged so that they are not in the sections of the walls that are to be cut away. Sections of the wall that consist of cement-board panels and foamed concrete can be easily removed using a circular saw equipped with a masonry blade. The reinforcing bar that runs horizontally in the center of the wall can be cleaned off and trimmed out with a metal saw. Where it can be anticipated that windows and door will produce extra stress in the wall, pilasters can be cast in the wall on either side of the position where the openings will be located. Conventional construction techniques can be used to frame windows and doors.

4 Development of Improved Panel Attachment System

The notched rod used in the initial wall assembly worked well, but has the following disadvantages:

a. Any changes in the wall thickness requires a tie rod with different dimensions in the notching system. The tie rods are set up for fixed thicknesses and cannot be adjusted to accommodate small changes that might be needed. This complicates manufacturing and stocking.

b. When the tie rod is installed and engages the wall panels, a gap results in the panels above the tie rods. These gaps have to be sealed if foamed concrete is used. Sealing can be accomplished, but it is an extra step in construction. The clip that fits over the tie rod assists in the sealing, but is an extra piece that must be installed during construction.

c. All of the ends of the tie rods have to be trimmed off when the wall is completed. The ends of the tie rods have to be smoothed down flush with the surface of the exterior panel to produce an attractive finish.

d. When the tie rods are trimmed flush with the wall, the mechanical engagement between the exterior panels and the rod are removed. The tie rods are still glued in place by the sealer, but a stronger attachment should produce a sturdier wall.

An additional fastener was developed to overcome these problems. The new fastener (U.S. Patent Office 1997b) is based on the concept of engaging two helical coils that are maintained in alignment using a central prong or an external tube (Figure 26). The design that uses the external tube with the coils inside is particularly useful in the wall construction because the tube can become a spacer between opposing exterior panels.

The helical fastener is an improvement because it can potentially make assembling the wall system simpler and can reduce costs of material. The new fastener offers advantages, including the following features:

a. It can have a flat or tapered end plate or cap that completely seals the holes in the exterior panels when it is installed, and no sealant or clips should be required to prevent concrete from leaking from the formwork.

b. It can form a permanent mechanical attachment to the panels. The cap can be countersunk into the exterior surface of the panels and will remain as a mechanical attachment between the panels.

c. The helical section of the fastener can be made by trimming commercially available steel springs. No machined parts are needed. The strength in tension can be determined by the type and size of the spring selected. The cap portion can be molded or bonded to the end of the spring. Manufacturing the fastener is very simple. The external tube can be cut from a variety of commercially available rigid metal or plastic tubes.

d. The fastener requires only one part. The pieces screw together, but there is no male or female. The two helical sections are identical. Fewer pieces have to be stocked, and the assembly of the wall is simpler than if threaded connectors were used.

e. The fastener can be made longer by adding a section of spring that threads onto the end of the existing spring and then adding a section of tubing. One fastener can be used on a variety of jobs.

g. The head of the fastener can be made flat or tapered and countersunk into the exterior panel so that the cap is flush with the surface. The flush installation reduces the effort necessary to produce a smooth finish on the panel.

The helical fastener can work very well with the corrugated separator used in the wall design that was developed in the research effort as a replacement for the tie rod system currently used. The assembly system that is outlined can be modified to accommodate a variety of form tie systems. Problems with regard to pressure from the foamed concrete can be addressed by placing the full height of the concrete in several lifts and allowing each lift to gain strength before the next lift is added. The spacing of the form ties or fasteners can be adjusted so that the pressure inside the form is divided over more support points.

5 Discussion

The goal of this investigation was the development of a system for building walls that uses foamed concrete cast between stay-in-place forms made from cement board (U.S. Patent Office 1995). The project included the design and development of:

a. A lightweight, fiber-reinforced concrete formulation that will develop an unconfined compressive strength over 690 kPa (100 psi) and a density below 640 kg/m^3 (40 lb/ft^3) that can be placed in lifts up to 2.42 m (8 ft) deep without collapse occurring.

b. A recommended method for the placement of the foamed concrete so as to form a uniform mass with no cold joints.

c. Methods of coating the panels to prevent loss of water into the panels during placement.

d. Methods of forming and reinforcing the foundation.

e. Methods of attaching the panels to each other and to the foundation.

f. Methods of producing strong columns (pilasters) of conventional concrete internal to the wall.

The wall design developed in this project is unusual in that it employs a number of simple concepts that have not been fully exploited in conventional construction, primarily the use of stay-in-place forms to cast the concrete and the use of light weight concrete in panels and conventional concrete in internal pillars (pilasters). The concept of a separator in the wall that ties the wall together and allows the forms to be attached to the outside without extensive bracing makes the system adaptable to conventional construction skill levels and conventional equipment. The wall construction system takes advantage of modern adhesives and sealers to bond the panels to the separators, at the same time the helical fasteners developed for the wall will hold the wall together with a mechanical link. The corrugated separator panel braces the wall at closely spaced points to assure that the wall panel remains flat and also

separates the interior of the wall into compartments that will allow utilities to be run in the wall just as in wooden stud construction.

The wall design is remarkably adaptable. All of the vertical load is carried on the steel-reinforced concrete pilasters that are tied into the foundation at the bottom of the wall and that are tied to a beam at the top that runs the length of the wall. Resistance to shearing deformation is provided by the panels between the beams. The mechanical properties of the wall can be readily changed by adjusting the dimensions of the pilasters and the beams. The system from a structural point of view is post-and-beam construction.

A variety of materials can be employed in the construction to vary the cost and the service life of the wall. The present project began by employing a cement board that is reinforced with a fiberglass mesh, but the test wall in the project was made with a cellulose-fiber-reinforced cement board. Trial wall assemblies have been prepared by using a separator panel that was made from cement board. The final test wall that was constructed used a corrugated separator that was made by bending sheet metal. Similarly, the notched tie rods were cut from wooden dowels, but plastic rods would have worked equally well. The trial helical fasteners were prepared from commercially available metal springs but could easily have been molded from a structural polymer such as nylon. Cellular concrete is the safest and most environmentally compatible panel filler material, but advances in pump-in urethane foams may make them a preferred material.

Construction techniques for the wall involve commonly available skills. The separator panels must be placed so that they are aligned and plumb. Panels are typically attached with a gap between the panels to allow for expansion. An elastomeric sealer is used to fill the joint and produce a final smooth finish. Panels must be trimmed, but there is no requirement for special precision. There is a requirement that they be made watertight because of the fluidity of the foamed concrete; this can be easily accomplished by applying sealer between the exterior panels and the separator panels. Production of the foamed concrete is the only unusual construction skill that is needed in producing a wall. While foamed concrete can be manufactured in a mortar mixer or even in a transit mixer; the best quality control is obtained if a mixer especially designed for cellular concrete is used by a contractor who is experienced in the production of this type of concrete for use in fire walls and roof decks.

The cost advantage of using this wall panel construction technique can be obtained in the materials and labor used in construction and the increased durability and fire resistance of the wall system. The building system produces an insulated, fire-resistant concrete wall with spaces developed for utilities in a single construction effort that does not require the construction or dismantling of formwork. The form provides a smooth concrete surface ready to finish with the minimum of skilled labor.

6 Conclusions, Recommendations, and Commercialization

Conclusions

This CPAR project was undertaken to test, demonstrate, and commercialize a new construction system for buildings. The new system employs stay-in-place forms made from fiberglass-reinforced cement boards that are erected in a specially designed concrete foundation and then filled with foamed concrete. The project included wall units and the systems for joining and anchoring the units.

The testing and demonstration activities show there are no major technological barriers that prevent the use of the wall construction system with foamed concrete and stay-in-place forms. All of the technical objectives of this project were accomplished.

a. A number of strong, lightweight, foamed-concrete formulations have been developed that can be used in a structural wall.

b. Cement-board stay-in-place formwork can be used with foamed concrete if the surfaces of the cement board that are in contact with the foamed concrete are coated so as to be impervious to the water in the fresh concrete.

c. A wall that can be used as a support member in residential and light industrial construction can be produced when interior concrete pillars (pilasters) are incorporated into the wall design.

d. Form tie rods and fasteners that can be advantageously used with a corrugated separator panel in the wall to make an easily assembled wall are available.

e. The corrugated separator concept can be used to handle the structural problems related to attaching adjacent panels, forming corners, and producing openings for doors and windows.

Data on materials costs collected prior to the initiation of this demonstration indicated that the new method would reduce the cost of a typical 163-mm- (6.5-in.-) thick wall by 20 to 30 percent relative to conventional wooden framing with wallboard or masonry construction. Data on construction labor requirements for the competing systems indicated the stay-in-place form system would increase labor productivity by 30 to 50 percent. Nothing in this demonstration effort changes these estimates.

Recommendations

On the basis of this demonstration, wall construction with the foamed concrete and stay-in-place forms is technically feasible. The construction system merits use and commercialization based on the anticipated superior performance (low maintenance and high durability) of the all-concrete wall system over competing systems. It is recommended that WES and the Industry Partner:

a. Continue efforts to bring this new technology to the attention of the building community.

b. Propose construction of this type of wall in other construction research programs where this type of wall construction would be advantageous due to its intrinsic safety in fire and penetration resistance.

c. Proceed to market the patented technology (U. S. Patents 5,639,195 and 5,657,601) related to the wall construction that was jointly developed during this demonstration through the mechanisms provided by the Domestic Technology Transfer Act of 1986 as implemented in Army Regulation AR 70-57.

Commercialization

The Industry Partner has undertaken a new economic evaluation of the construction system and has determined that currently wall construction represents a small fraction of the cost of most new residential and light-industrial construction and any savings from using this construction system would have little impact on the overall cost of any typical construction project. Attempts to immediately commercialize the wall construction system have not been successful due to the increased building costs. When the wall system was originally proposed for demonstration, the cost of raising the walls of a building represented approximately 7.7 percent of the total building

construction. The walls now account for less than 5.6 percent of the total costs of building. Commercialization of this wall construction system will necessarily be pursued on the basis of the special characteristics of the wall system rather than an immediate increase in profits realized in construction.

The WES will make the new technology that the Army owns available for licensing. Under the terms of the CPAR-CRADA, the Industry Partner owns a non-exclusive license to all jointly developed technology. The Industry Partner can use all proprietary technology and can make the technology available in sub-licensing agreements.

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Table 1
Foamed-Concrete Mixtures Used in Tests with 406-mm-Diameter Columns

Test No.	Date Cast	Silica Fume Replacement % Cement	Water/Cement & Silica-Fume Ratio	HRWRA[1] Type	Type of Foaming Agent	Remarks
16	6/1/95	0	0.61	P-169	Litecrete[2]	
12	5/22/95	0	0.62	P-169	Litecrete	
13	5/23/95	0	0.62	S-300	Litecrete	
20	6/12/95	10	0.48	S-10	Litecrete	Cement dropped out
23	6/20/95	10	0.55	S-10	Litecrete	Column and panel cast
15	5/24/95	10	0.61	S-300	Litecrete	
30	9/7/95	10	0.62	S-10	Litecrete	Column and panel cast
14	5/24/95	10	0.70	P-169	Litecrete	
17	6/2/95	20	0.61	P-169	Litecrete	
18	6/5/95	20	0.61	S-300	Litecrete	Column collapsed
19	6/5/95	20	0.62	S-300	Litecrete	Column collapsed

[1]P-169 = Plastocrete 169, Sika Corp., Lyndhurst, NJ.
S-300 = Sikament 300, Sika Corp., Lyndhurst, NJ.
S-10 ESL = Sikament 10 ESL, Sika Corp., Lyndhurst, NJ.

[2]Litecrete = Litecrete Foaming Agent, Insulcrete Inc., Rosemead, CA.

Table 2
Densities and Unconfined Compressive Strenghts Obtained from Cured Foamed-Concrete Samples from 406-mm-Diameter Columns

Test No.	Density		Unconfined Compressive Strength		Density		Unconfined Compressive Strength	
	kg/m^3	(lb/ft^3)	kPa	(psi)	kg/m^3	(lb/ft^3)	kPa	(psi)
0% Silica Fume								
16	392.5	(24.5)	344.7	(50)	397.3	(24.8)	461.9	(67)
12	416.5	(26.0)	227.5	(33)	422.9	(26.4)	344.7	(50)
13	456.6	(28.5)	613.6	(89)	435.7	(27.2)	703.2	(102)
10% Silica Fume								
20	379.7	(23.7)	68.9	(10)	370.1	(23.1)	96.5	(14)
23	544.7	(34.0)	351.6	(51)	541.5	(33.8)	923.9	(134)
15	463.0	(28.9)	661.9	(96)	447.0	(27.9)	951.5	(138)
30	575.1	(35.9)	1102.4	(160)	547.9	(34.0)	1722.5	(250)
14	440.6	(27.5)	213.7	(31)	424.5	(26.5)	351.6	(51)
20% Silica Fume								
17	463.0	(28.9)	710.2	(103)	443.7	(27.7)	958.4	(139)
18	Column collapsed							
19	Column collapsed							

Table 3
Characteristics of Foamed Concrete Used in Tests with Cement Board Panels

Test No.	Date Cast	Silica Fume Replacement % Cement	Water/Cement & Silica-Fume Ratio	HRWRA[1] Type	Type of Foaming Agent	Remarks
31	10/13/95	0	0.44	S-10	L	
32	10/13/95	0	0.44	S-10	L	
33	10/23/95	0	0.44	S-10	L	Lost fiber in pump
34 I	10/24/95	0	0.44	S-10	L	Panel coated on inside
34 O	10/24/95	0	0.44	S-10	L	Panel coated on outside
21	6/14/95	0	0.48	S-10	L	Panel collapsed
22	6/16/95	0	0.48	S-10	L	
35 I	10/25/95	0	0.50	S-10	L	Panel coated on inside
35 O	10/25/95	0	0.50	S-10	L	Panel coated on outside
36	11/14/95	0	0.50	S-10	L	Panel collapsed
24	8/15/95	0	0.51	S-10	L	Panel collapsed
23	6/20/95	0	0.55	S-10	L	
37	11/28/95	0	0.57	S-10	L	Panel collapsed
38	12/1/95	0	0.51	S-10	L	Panel collapsed
26	8/24/95	0	0.61	S-10	L	Form failed
25	8/18/95	0	0.62	S-10	L	
27	9/1/95	0	0.62	S-10	L	Panel collapsed
28	9/1/95	0	0.62	S-10	L	Panel collapsed
29	9/7/95	0	0.62	S-10	L	
30	9/8/95	0	0.62	S-10	L	
39	12/1/95	0	0.57	S-10	W	Lost cement from suspension
40	12/11/95	0	0.57	S-10	W	
41	12/13/95	0	0.57	S-10	W	
42 I	1/11/96	0	0.61	S-10	W	Panel coated on inside
42 O	1/11/96	0	0.61	S-10	W	Panel coated on outside
43	1/22/96	0	0.61	S-10	W	

[1]S-10 = Sikament 10 ESL, Sika Corp., Lyndhurst, NJ.
L = Litecrete Foaming Agent, Insulcrete Inc., Rosemead, CA.
W = SF-304 Foaming Agent, Cellufoam Concrete Systems, Inc., Scarbrough, Ontario, Canada.

Table 4
Densities and Unconfined Compressive Strengths Obtained from Cured Foamed-Concrete Samples Between Cement-Board Panels

Test No.	Samples Cured for 7 days				Samples Cured for 28 days			
	Density		Unconfined Compressive Strength		Density		Unconfined Compressive Strength	
	kg/m³	(lb/ft³)	kPa	(psi)	kg/m³	(lb/ft³)	kPa	(psi)
31	533.5	(33.3)	268.7	(39)				
32	769.0	(48.0)	2397.7	(348)				
33	225.9	(14.1)	778.6	(113)				
34 I	398.9	(24.9)	330.7	(48)	342.8	(21.4)	385.8	(56)
34 O	416.5	(26.0)	323.8	(47)	374.9	(23.4)	379.0	(55)
21		Collapsed						
22	536.7	(33.5)	537.4	(78)	483.8	(30.2)	909.5	(132)
35 I	427.7	(26.7)	399.6	(58)	368.5	(23.0)	468.5	(68)
35 O	400.5	(25.0)	282.5	(41)	379.7	(23.7)	330.7	(48)
36		Collapsed						
24		Collapsed						
23	544.7	(34.0)	351.4	(51)	541.5	(33.8)	799.2	(116)
37		Collapsed						
38		Collapsed						
26		Form failed						
25	480.6	(30.01)	316.9	(46)	480.6	(30.0)		(145)
27		Collapsed						
28		Collapsed						
29	491.8	(30.7)	654.6	(95)	501.4	(31.3)	999.1	(193)
30	560.7	(35.0)	1150.6	(167)	547.9	(34.2)	1743.2	(253)
39	309.2	(19.3)	82.7	(12)	368.5	(23.0)	103.3	(15)
40	463.0	(28.9)	406.5	(59)				
41	387.7	(24.2)	117.1	(17)	347.6	(21.7)	144.7	(21)
42 I	567.1	(35.4)	1267.8	(184)	496.6	(31.0)	1626.0	(236)
42 O	576.7	(36.0)	1171.3	(170)	512.6	(32.0)	1743.2	(253)
43	586.3	(36.6)	730.3	(106)	499.8	(31.2)	1219.5	(177)

Table 5
Peak Temperatures Recorded in Columns and Panels of Foamed Concrete

Test No.	Sample Type	Date Cast	Peak Interior Temperature		Peak Ambient Temperature		Remarks
			°C	°F	°C	°F	
14	Column	5/24/95	39	102	22	72	
15	Column	5/25/95	36	97	22	72	
16	Column	6/1/95	36	97	21	70	
17	Column	6/2/95	39	102	21	70	
18	Column	6/5/95	40	104	22	72	
19	Column	6/9/95	38	100	22	72	Lost cement
20	Column	6/12/95	39	102	21	70	
22	Panel	6/16/95	54	129	22	72	
23	Panel	6/20/95	54	129	22	72	
25	Panel	8/18/95	52	125	22	72	

Table 6
Optimum Concrete Mixture

Material	Mass/Volume
Portland Cement, Type I	78.2 kg (472 lb)
Silica Fume, 10% of Cement	7.82 kg (47.2 lb)
Water	95 kg (209 lb)
Actual Water/Cement Ratio	0.50
HRWRA	2.4 L
Stabilizer	113 g
Nylon Fiber	453.6 g
Preformed Foam	0.57 m^3 (20.11 cf)

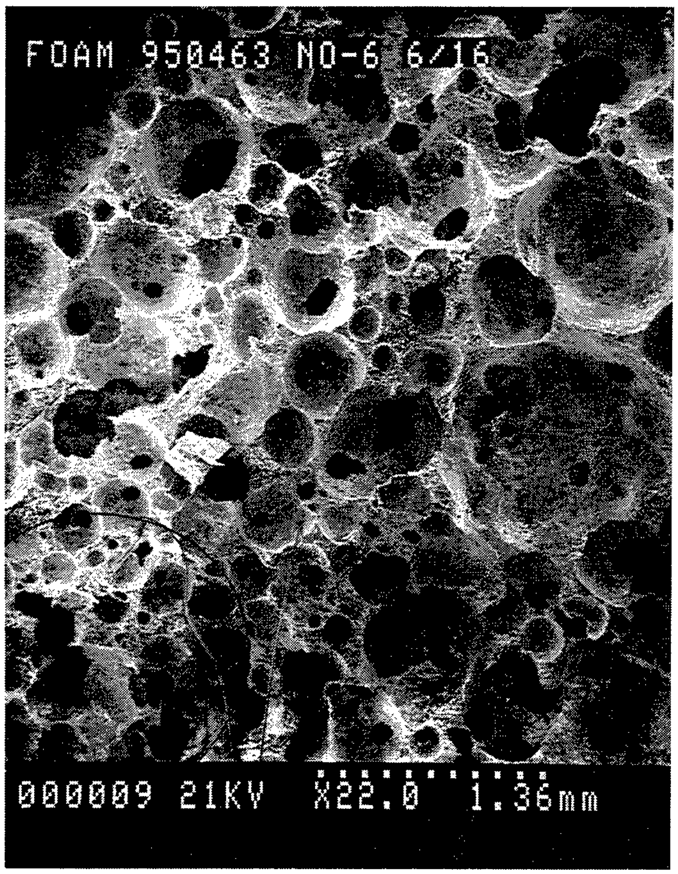


Figure 1. Photomicrograph of foam concrete

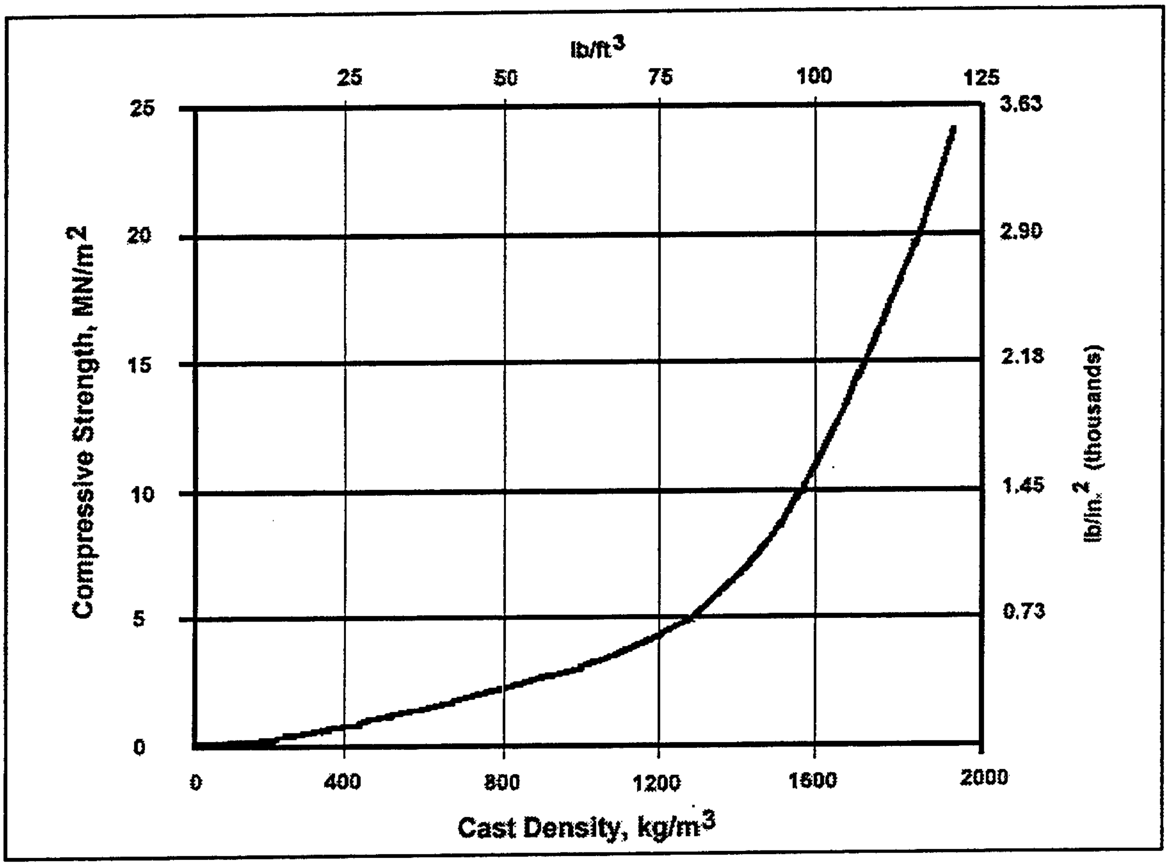


Figure 2. Strength versus density for foamed concrete (after Legatski (1994))

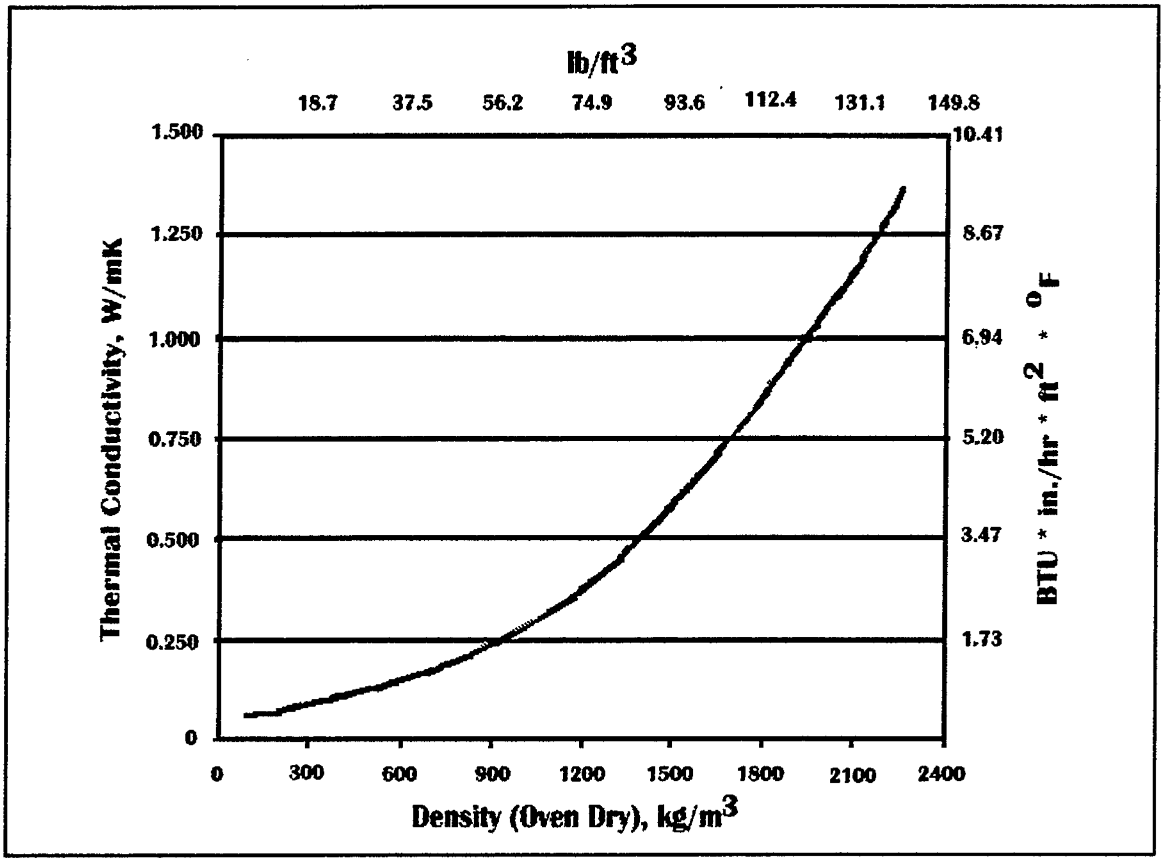


Figure 3. Thermal conductivity versus density for foamed concrete

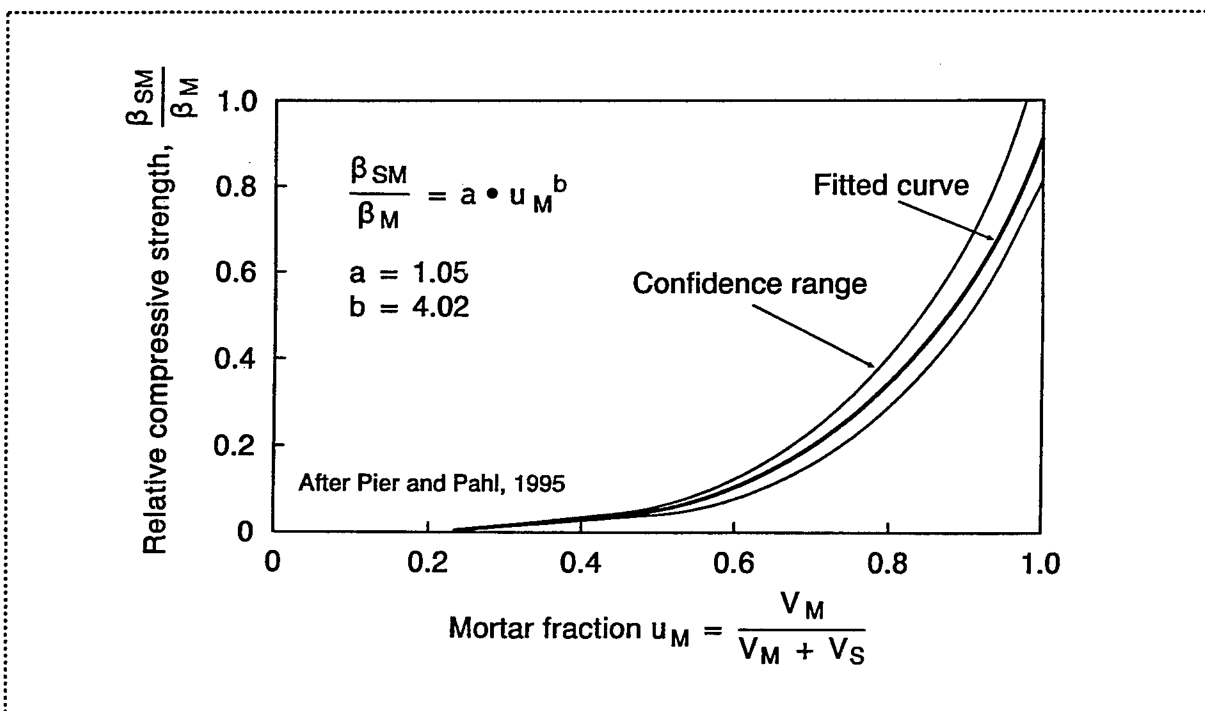


Figure 4. Strength of foamed concrete versus volume fraction of paste (after Pier and Pahl (1994)

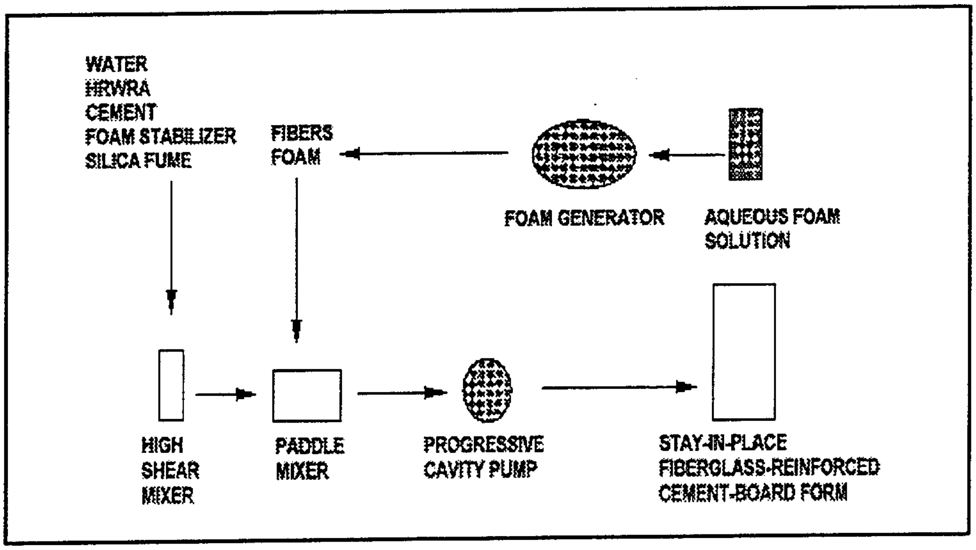


Figure 5. Steps in preparing concrete for test columns and panels

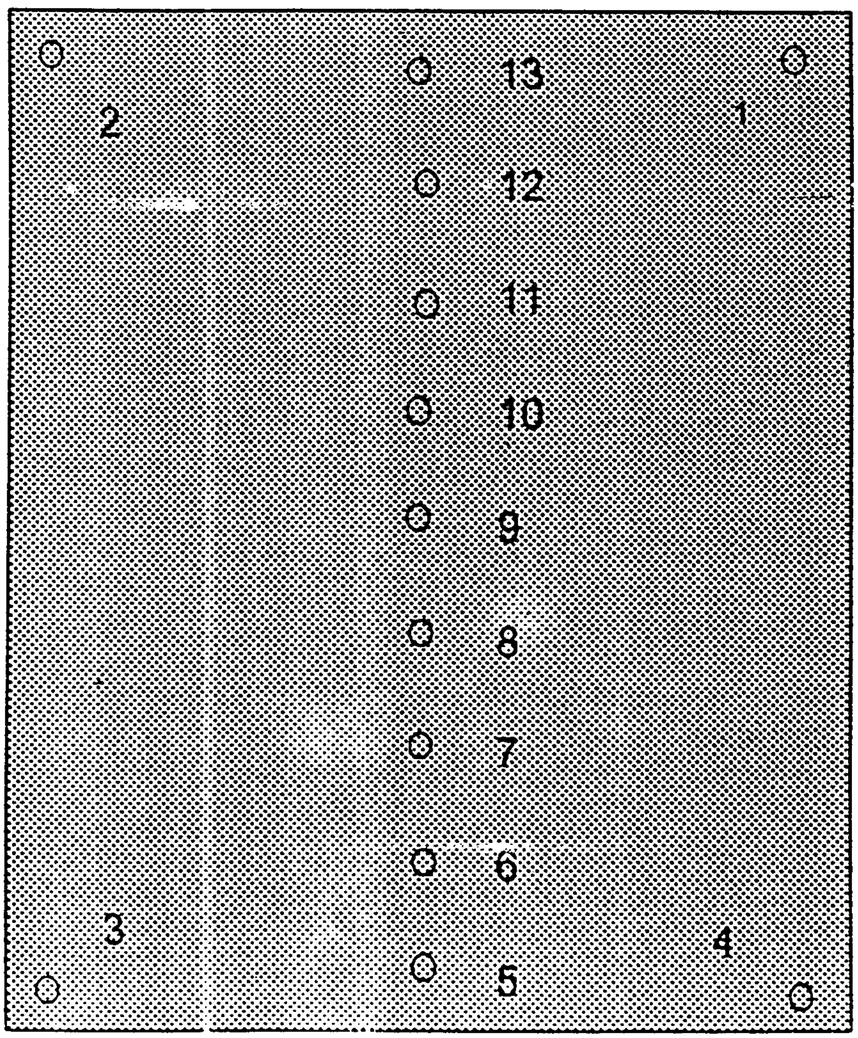


Figure 6. Pattern thermocouple placement in the test panels

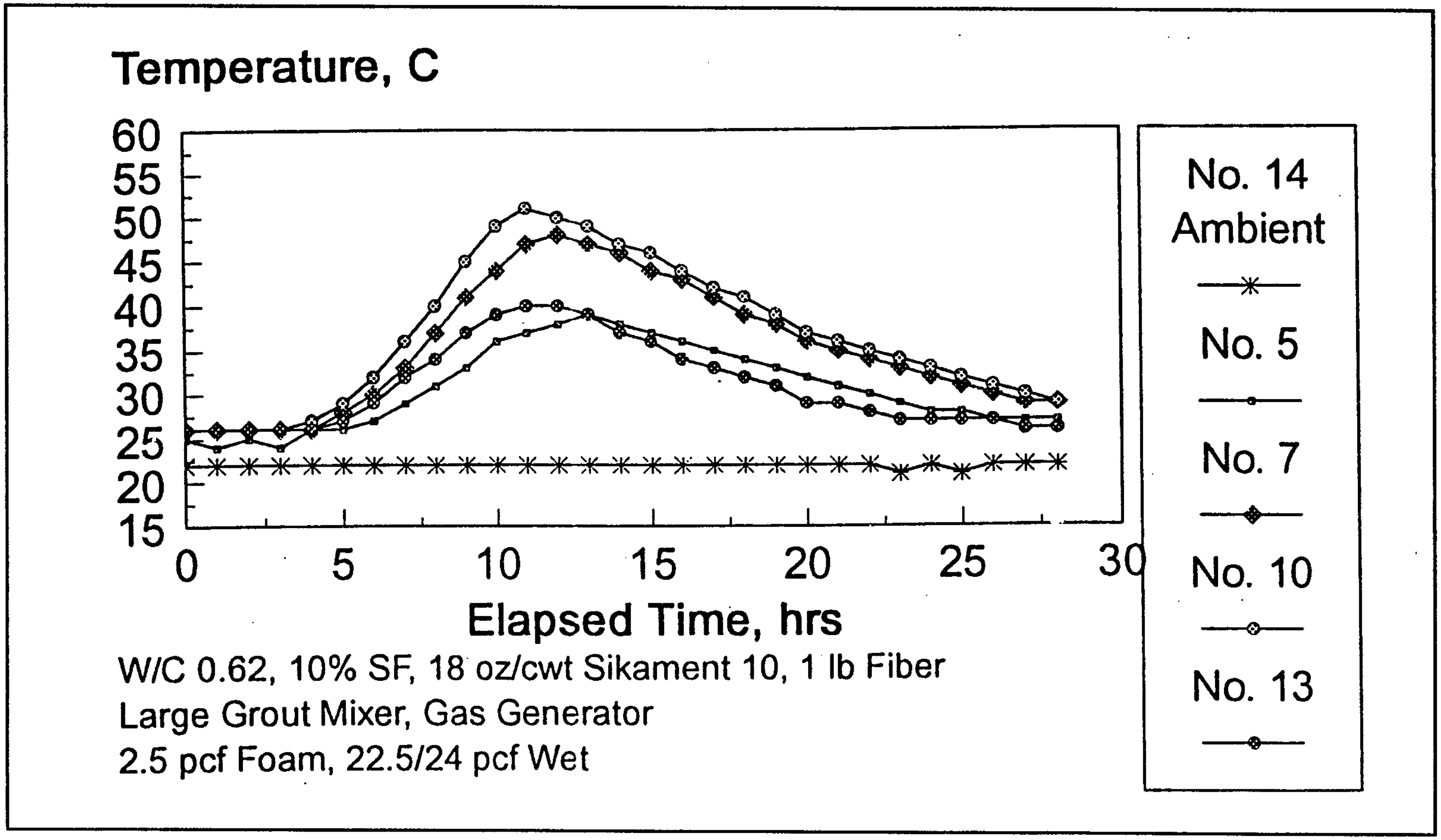


Figure 7. Temperature records for thermocouples placed in Test 25

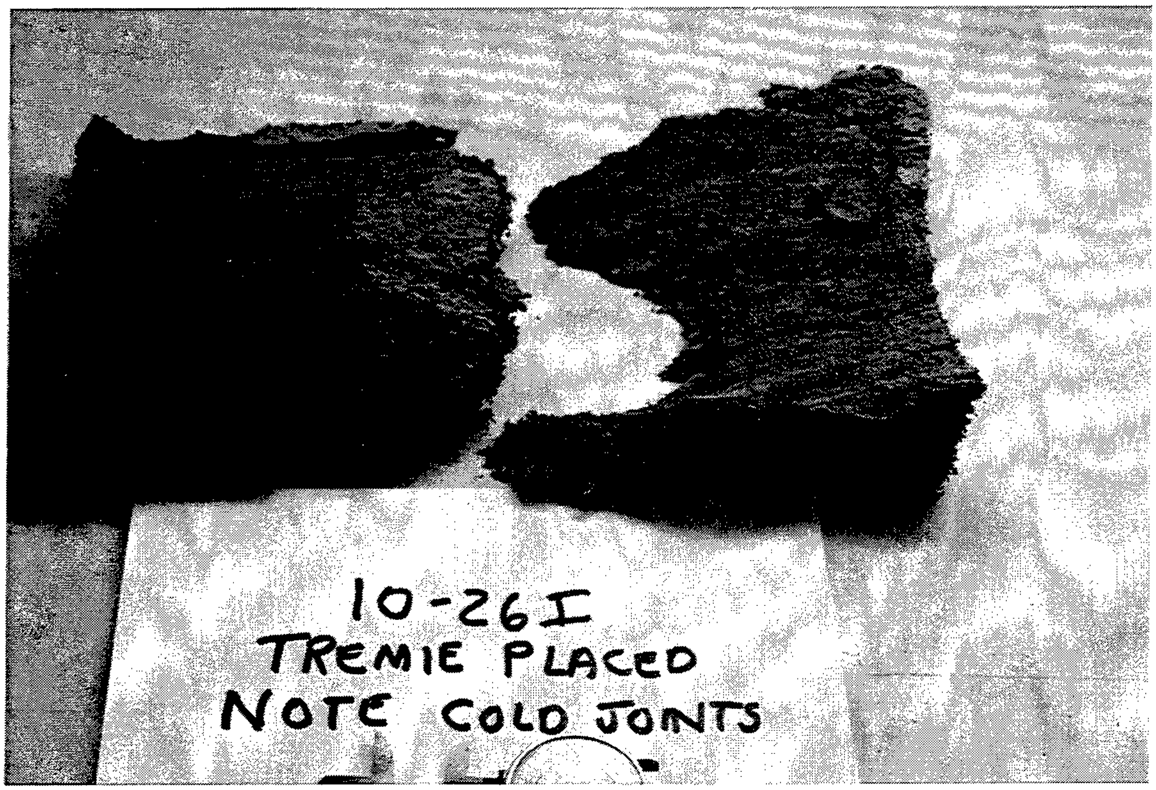


Figure 8. Failure surfaces in foamed-concrete samples

Figure 9. Leakage that occurs in uncoated cement-board panels

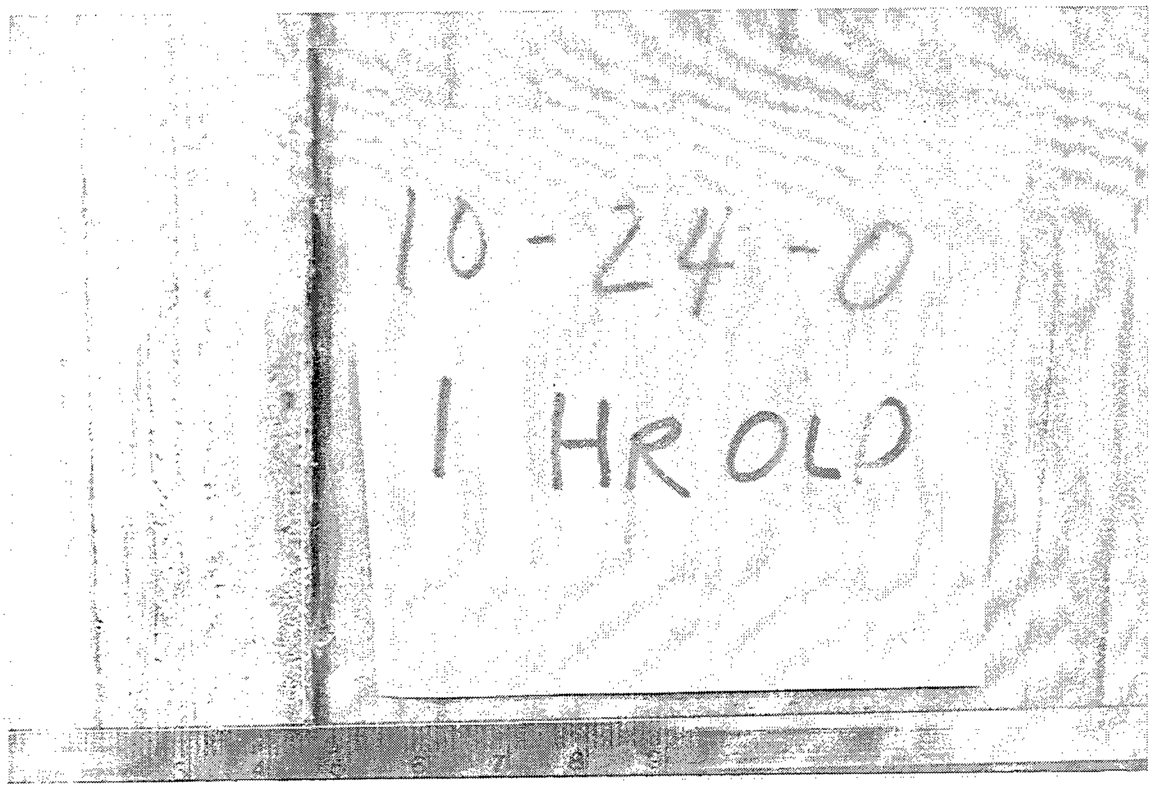


Figure 10. Cement-board formwork coated on the outside shows moisture penetration approximately 5 mm into the cement board 1 hr after placement

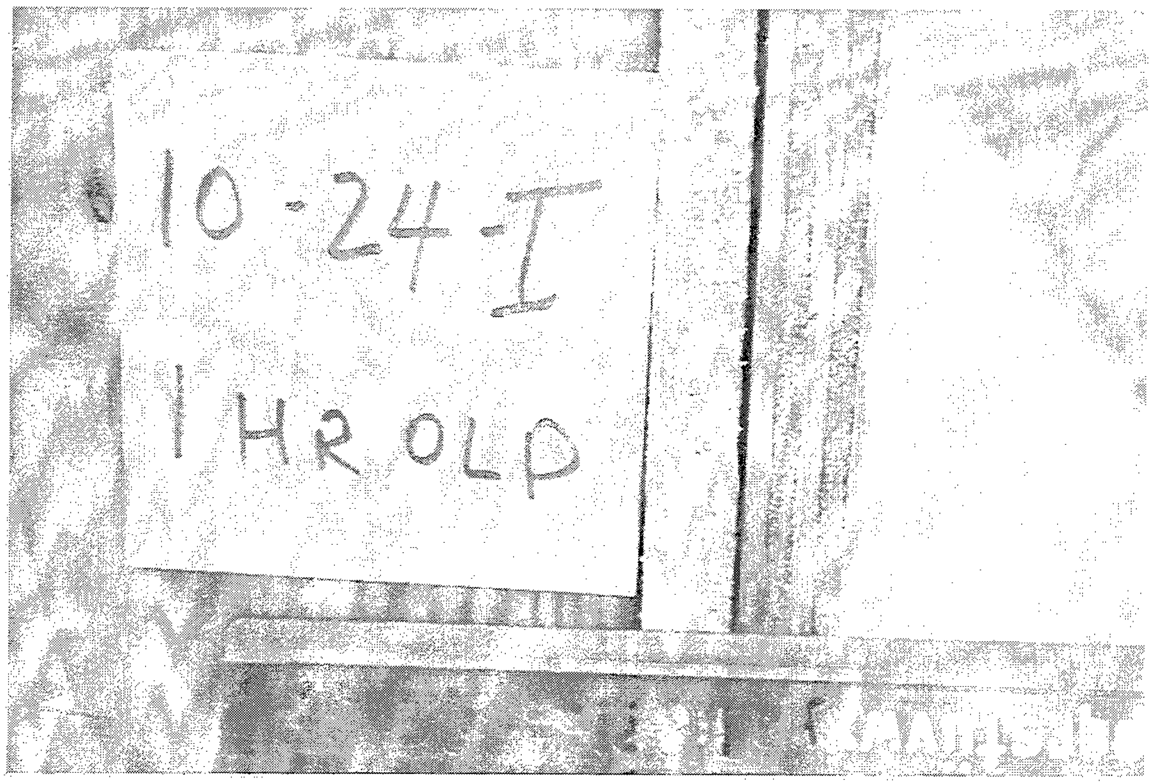


Figure 11. Cement-board formwork coated on the outside shows moisture penetration 1 hr after placement of foamed concrete

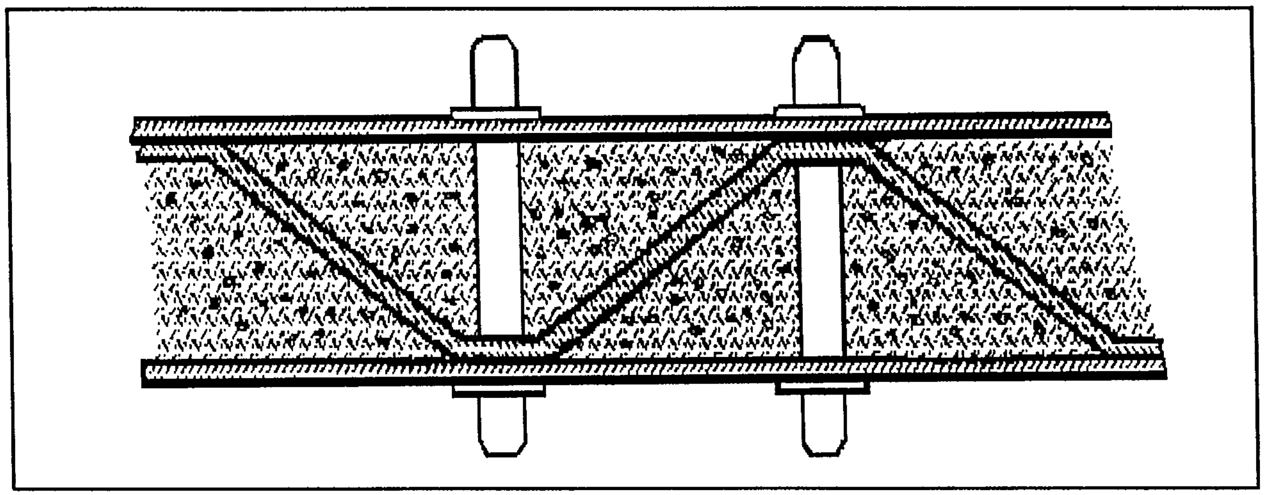


Figure 12. Position of separator panel between exterior panels

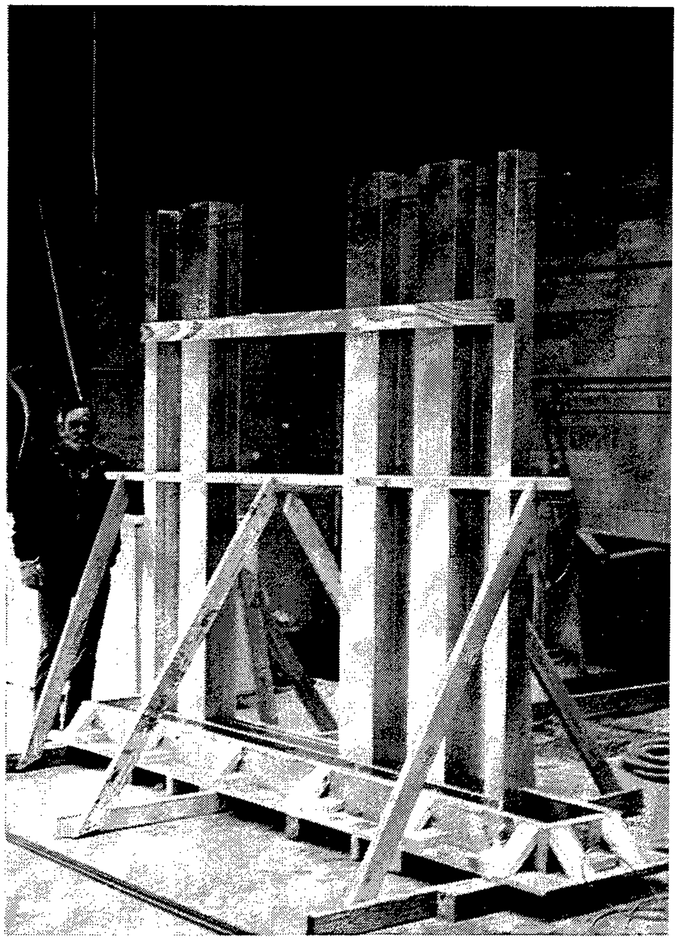


Figure 13. Metal panels held in position in formwork

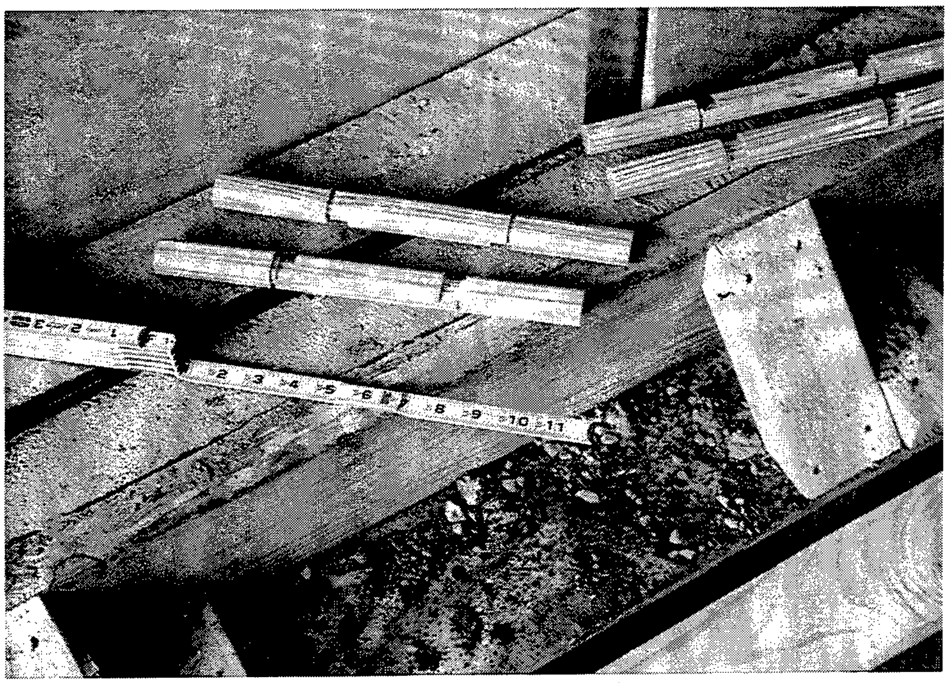


Figure 14. The rods used to attach exterior panels

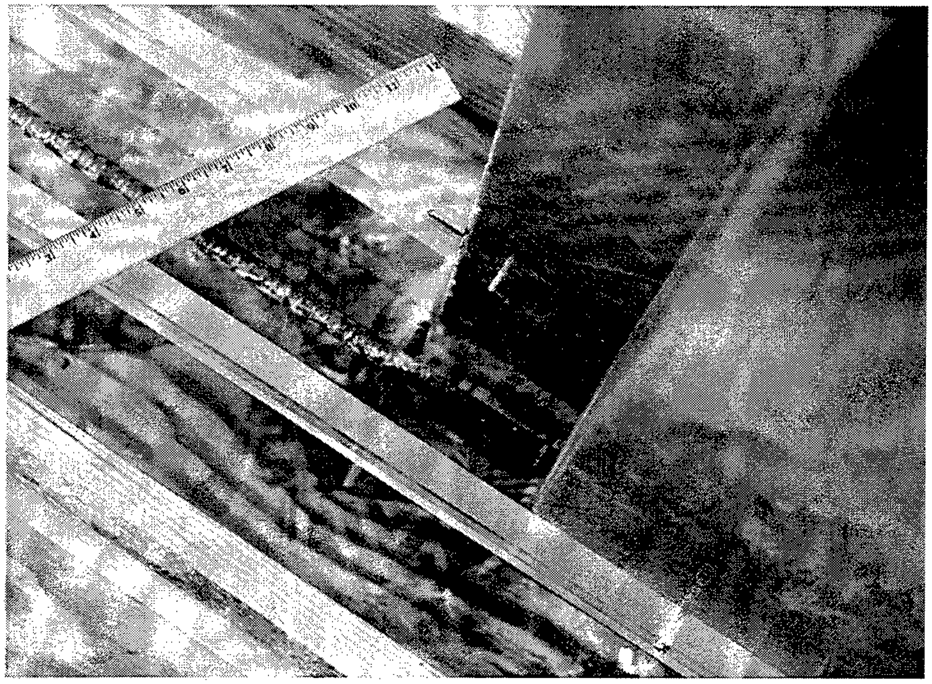


Figure 15. Wire chair holding the separator panel

Figure 16. Lower reinforcing rod centered in the formwork for the footing

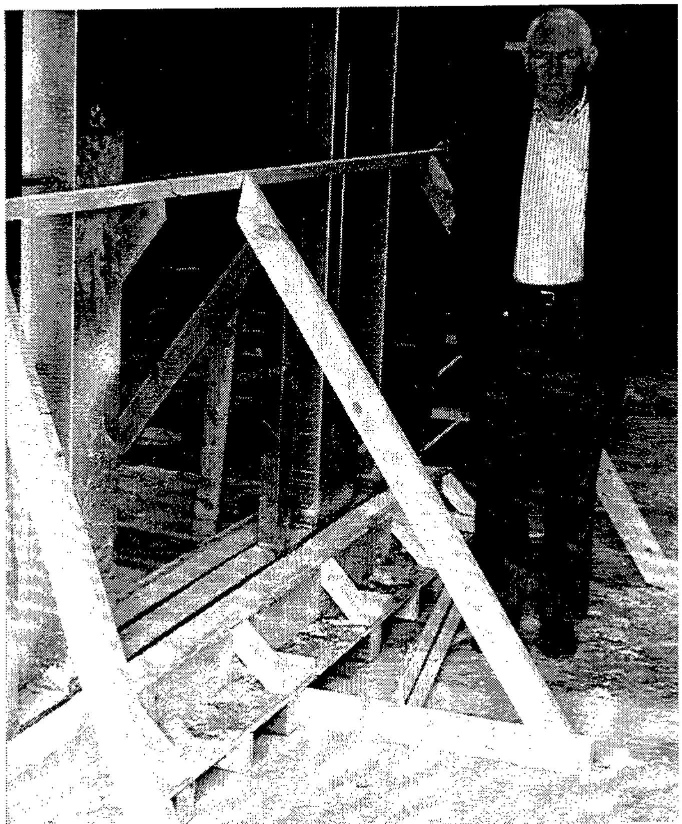


Figure 17. Temporary bracing used to hold the separator panels in the formwork

Figure 18. Plastic strip used as blockout in the top of the footing

Figure 19. Groove produced by blockout used in footing

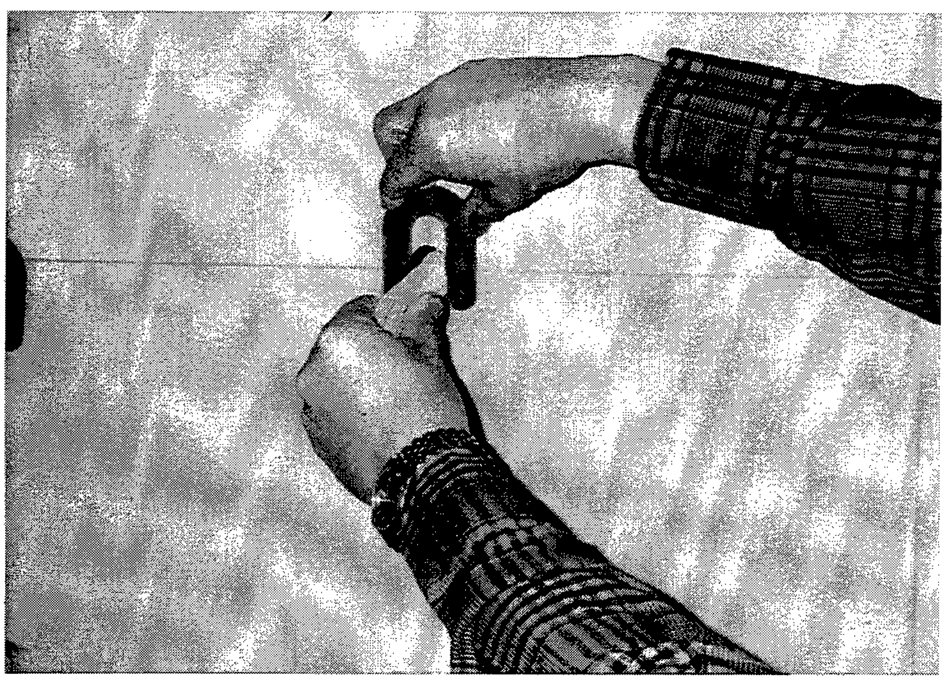


Figure 20. Notched tie rod engaging the edges at the borehole

Figure 21. Corner column of spacer panel

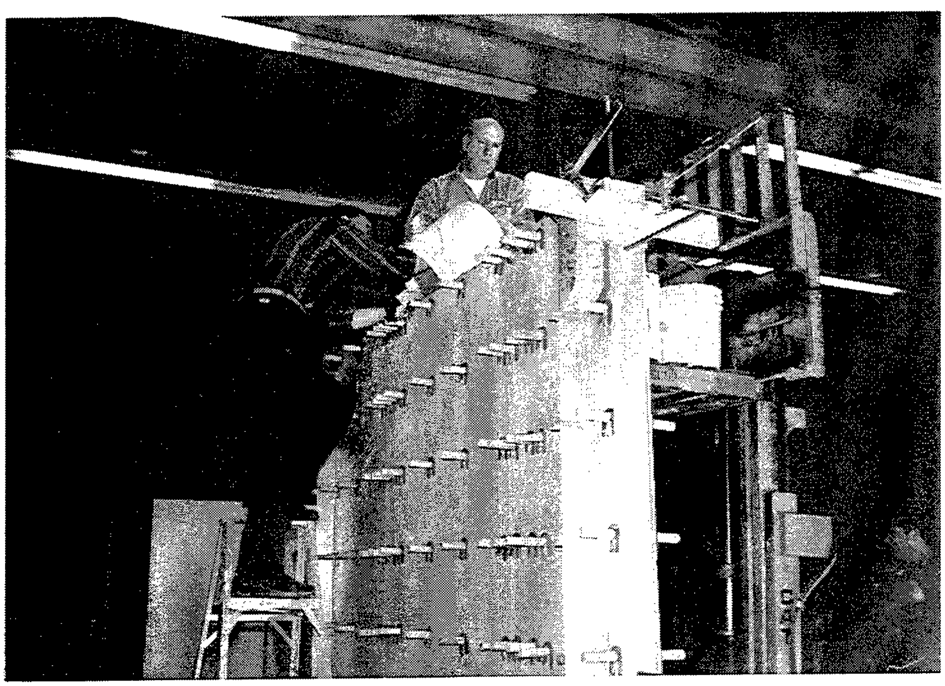
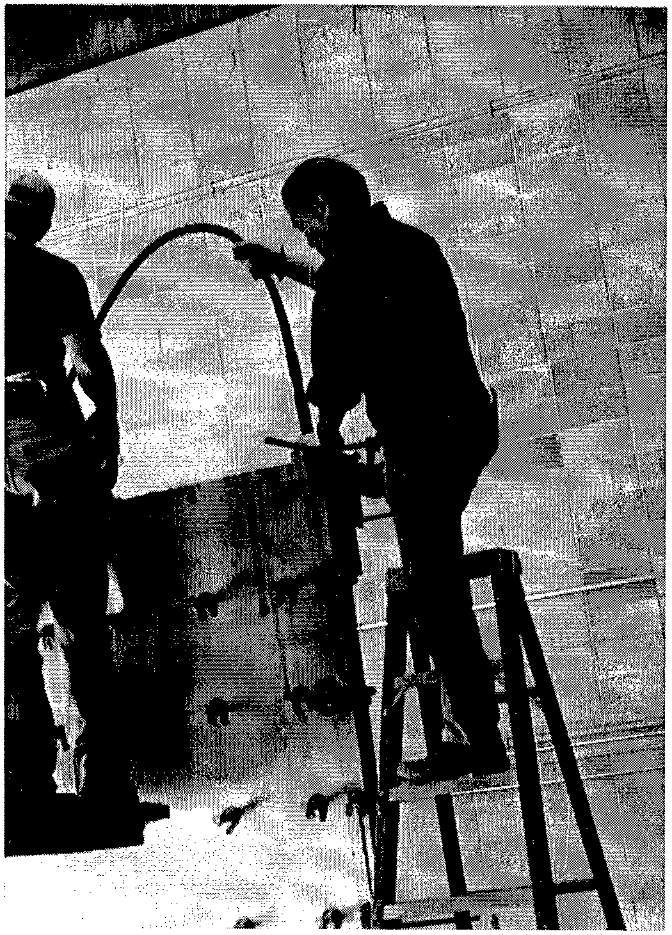


Figure 22. Filling compartments stay-in-place forms with foamed concrete



a. View from corner of form

b. View from top of form

Figure 23. Consolidating the concrete beam at the top of the wall

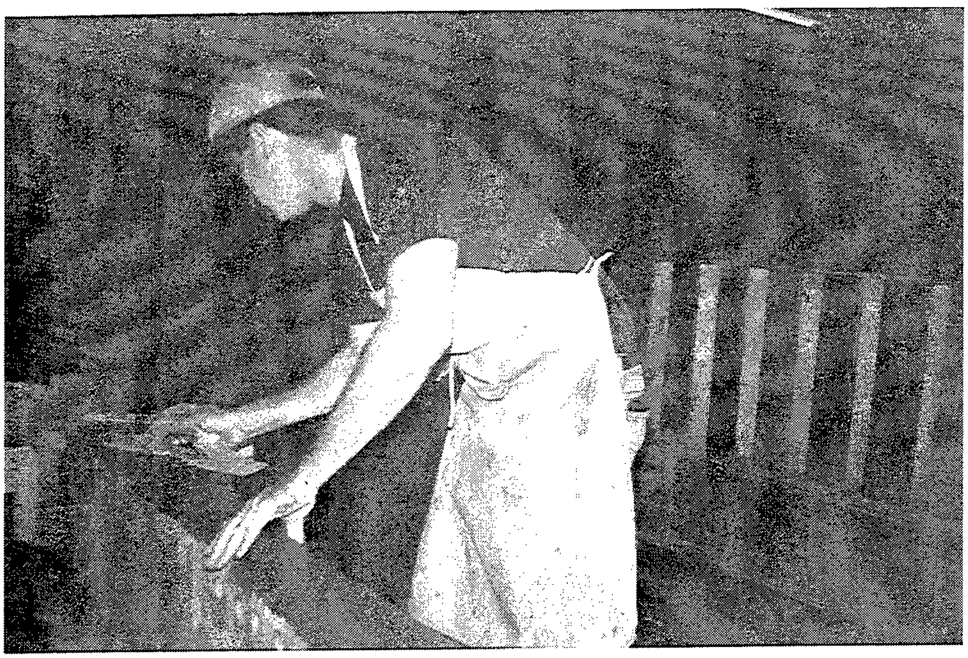


Figure 24. Finishing the toe of the concrete used in the pilasters

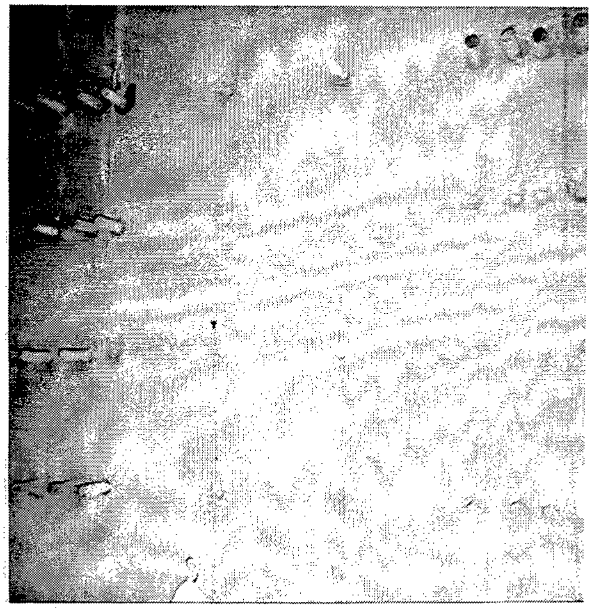


Figure 25. Wall surface after the ends of the tie rods are trimmed off

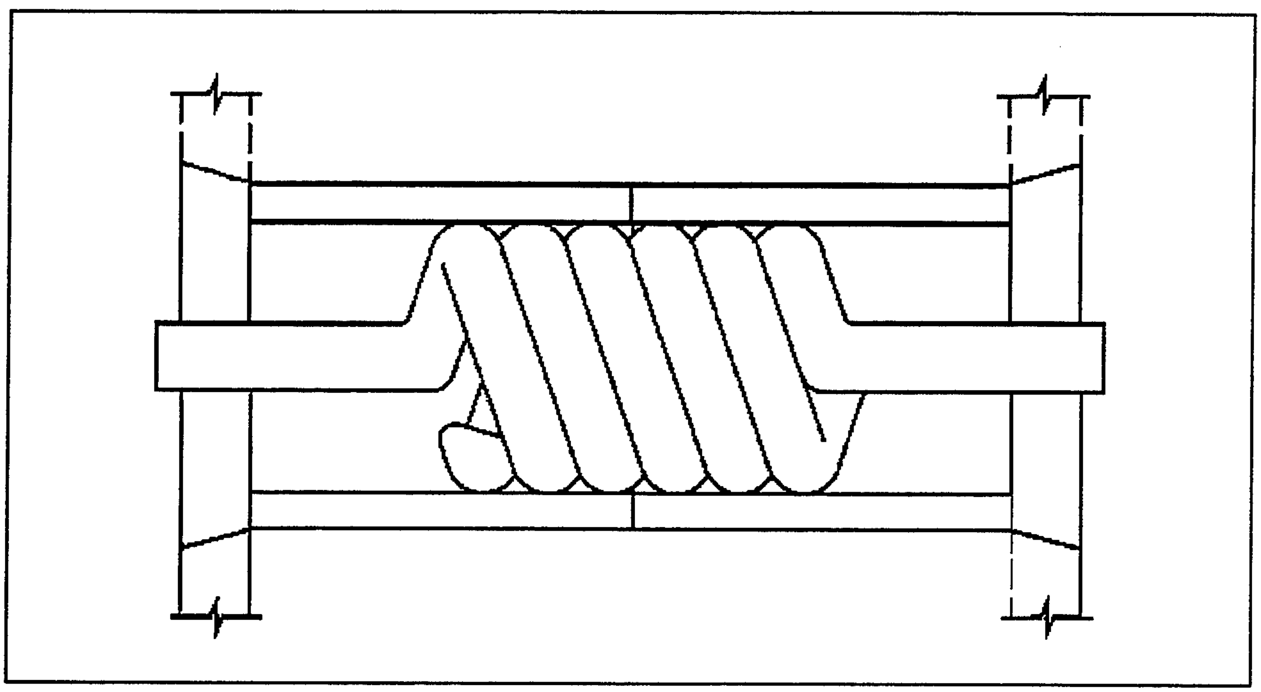


Figure 26. Drawing of the helical fastener

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13. ABSTRACT (Maximum 200 words)

In January 1995 a Construction Productivity Advancement Research (CPAR) program agreement between Materials Technology Ltd. (MTL), Reno, NV, and the U.S. Army Engineer Waterways Experiment Station (WES) was initiated. The purpose was to develop a new system of building walls for residential and light-utility buildings. The new approach used stay-in-place, fiber-reinforced cement-board forms with foamed or cellular concrete cast between the forms. An immediate goal of the research was to prepare a formulation for cellular concrete that could be cast between cement-board forms in lifts as thick as 2.42 m and to optimize the mixture in terms of cost and strength. The project also involved investigating the compatibility of the formulation that was developed with the cement board and developing the optimum system for placing the foamed concrete in the forms. WES collaborated with the industry partner in developing an improved panel spacer and form tie system and further assisted by developing a versatile, low-cost panel fastening system that can be used with the stay-in-place forms. Because of the potential benefits of this developing technology for both the Federal Government and the private sector, this research on a new building system was well-suited to the CPAR Program.

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